Optimizing Weed Suppression Via Cover Crop and Herbicide Programs in the Mid-Atlantic

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Academic Abstract

Many Virginia farmers include cover crops in their corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) production due to government subsidies and agronomic benefits. Progressive farmers have optimized cover crop management for specific goals, such as weed suppression and nitrogen fertilizer reductions. Waiting to terminate the cover crop until cash crop planting, so-called "planting green," is often part of the management and is an evolution from the traditional termination timing prior to cash crop planting. To scientifically scrutinize these production systems, three research objectives were developed. These objectives included determining if these systems lead to greater biomass accumulation, increase overall weed suppression, and reduce herbicide inputs.

The goal of our first experiment was to determine if a hairy vetch (*Vicia villosa* R.) and cereal rye (*Secale cereale* L.) mixture, where the cereal rye was selectively terminated in March, performed better than a hairy vetch monoculture for biomass accumulation and weed suppression. Results indicated that hairy vetch monocultures typically produced greater hairy vetch biomass throughout the season, had greater nitrogen contents, and provided similar weed suppression. Overall, a hairy vetch monoculture cover crop can substitute for a hairy vetch + cereal rye mixture, when the cereal rye is selectively terminated, while providing similar or greater benefits to the following cash crop.

Our second objective compared 1-, 2-, and 3-pass herbicide programs initiated either two weeks prior to, or at, corn planting paired with either hairy vetch, hairy vetch + cereal rye, or a

winter fallow to determine if herbicide input reductions are possible. We determined a reduction from a 3- pass to a 2- pass herbicide program is possible, however, at least a 2-pass program is needed for season-long weed suppression. Also, herbicide programs that terminated the cover crop at planting (i.e. planted green) tended to provide as good or better weed suppression compared to cover crops terminated prior to planting.

While cereal rye is a very popular species for cover cropping, farmers have reported nitrogen immobilization and planting problems because of its extensive biomass and high C:N ratio. Due to this, farmers are interested in substituting black oat (*Avena strigosa* S.) for cereal rye. Therefore, we conducted two experiments to compare cover crop characteristics. In corn, cereal rye, cereal rye + hairy vetch, black oats, and black oat + hairy vetch were compared while in soybean, black oat and cereal rye treatments were compared. Our results for both experiments indicated that cereal rye and black oat monocultures are similar in terms of lignin content and C:N ratio at cash crop planting. However, black oat treatments typically produced less biomass and suppressed fewer weeds compared to cereal rye treatments. This trend was also seen when comparing the black oat and hairy vetch mixture to the cereal rye and hairy vetch mixture. Ultimately, regardless of cash crop, farmers may still prefer to use a cereal rye monoculture or mixture as their cover crop.

Overall, the results of these experiments show that hairy vetch monocultures have the potential to increase weed suppression, nitrogen output, and biomass accumulation compared to hairy vetch and a grass cover crop mixture. However, farmers who include a grass species may lean towards cereal rye because of its benefits over black oats.

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General Audience Abstract

Cover crops are plants that are grown during the off seasons of main crops, such as corn (*Zea mays* L.) or soybean (*Glycine max* (L.) Merr.). These crops are not grown for profit, but rather because of benefits for crop production like weed suppression or nutrient output. Government subsidies associated with certain cover crops have also helped them gain popularity in Virginia. Recently, more Virginia farmers have started using specific cover crops to achieve certain outcomes such as reducing the need for fertilizer and/or herbicides. To try to capitalize on these benefits, farmers often wait to kill their cover crops until cash crop planting, also known as "planting green." This timing differs from the traditional management when cover crops are killed prior to cash crop planting. Many corn farmers in Virginia have opted to use either hairy vetch (*Vicia villosa* R.) alone or a hairy vetch and cereal rye (*Secale cereale* L.) mixture as a cover crop. Currently, little research has been done on the impact of planting green into hairy vetch monocultures or mixtures in Virginia. Therefore, to better characterize these practices, experiments were conducted.

Progressive corn farmers who plant a hairy vetch and cereal rye mixture cover crop and terminate only the cereal rye in March which leaves the hairy vetch to keep growing until corn planting. This method allows the farmer to maximize the benefits from the hairy vetch such as weed suppression and nitrogen output while avoiding issues associated with cereal rye. Our analysis of this system found that hairy vetch alone produced larger amounts of hairy vetch biomass throughout the season, had more potential fertilizer reductions, and could provide

similar weed suppression compared to the hairy vetch and cereal rye mixture. Thus, we determined that hairy vetch alone could be a substitute for the hairy vetch and cereal rye mixture, when the cereal rye is selectively terminated, and still provide similar if not better benefits to the following corn crop.

Many corn farmers in Virginia have reported being able to reduce herbicide use due to the weed suppression provided by cover crops. Thus, our second experiment was comparing 1-, 2-, and a 3- pass herbicide programs in either no cover crop, hairy vetch only, or a hairy vetch and cereal rye mixture to determine if reducing herbicide inputs is possible. A reduction from a 3-pass to a 2-pass can be possible without a loss of weed control. We also saw that herbicide programs that enable the corn to be planted green tended to result in greater weed control compared to cover crops terminated prior to planting.

While cereal rye is a popular cover crop in Virginia, farmers have reported planting issues and potential increases in fertilizer needs. Black oats (*Avena strigosa* S.) is a potential substitute for addressing these issues. Thus, we compared black oat, cereal rye, and then either paired with hairy vetch in corn and black oats and cereal rye alone in soybean. Cereal rye and black oats alone tended to have similar chemical compositions at cash crop planting. We also saw that black oats typically produced lesser amounts of biomass and suppressed fewer weeds compared to cereal rye. Similar results were seen with treatments containing hairy vetch. Overall, farmers in Virginia may still favor cereal rye alone or within a mixture over black oats, regardless of the following cash crop.

Ultimately, our research concluded that a cover crop of hairy vetch alone typically leads to greater biomass accumulation, nitrogen accumulation, and weed suppression compared to a hairy vetch and grass species mixture. However, if farmers intend to add a grass species, cereal

rye may be more favorable due to its greater benefits compared to black oats. Farmers may want to add a grass cover crop to increase the overall cover crop's biomass, reduce soil erosion, and offset costs due to associated government subsidies.

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Literature Review

Cover Crop Definition

For many years, certain plant species have been used to cover fallow fields in agriculture. These crops have been called many names including green manure, intermediate crops, catch crops, living mulch, and smother crops (Barnes and Putnam, 1983; Kaaspar and Singer, 2011). Today, they are commonly referred to as cover crops. Mutch and Martin (1998) define cover crops as "a crop that is not harvested but is grown to benefit the soil and/or other crops in a number of ways." No matter their name, cover crops can create healthier soil, provide nutrients to subsequent crops, suppress weeds, and better the environment around them. Over the past few years, the use of cover crops in cropping systems has increased (Wallander et al., 2021). Because of this, extensive research has been conducted focusing on the environmental, economic, and agronomic benefits as well as drawbacks of cover crops.

Advantages and Disadvantages

Reduced Erosion

Soil erosion negatively impacts crop productivity each year by lowering the water holding capacity, nutrients, and/or other resources in the remaining soil (Chen et al., 2022). Many farmers implement cover crops into their crop rotations to lessen erosion's impact on their cash crops (Wayman et al., 2017). By adding a vegetation layer on the soil surface, the impact of rainfall and the degradation of soil aggregates is reduced (Chen et al., 2022). The roots of cover crops also aid in preventing erosion by increasing water infiltration and making the soil more stable (De Baets et al., 2011; Gyssels et al., 2005). Grass roots have been found to be better soil stabilizers compared to other plant type roots (Gyssels et al., 2005; Saadati et al., 2023).

Minimizing sediment runoff may also aid in the prevention and/or reduction in nonpoint-source pollution (Blanco-Canqui, 2018).

Reduced Nutrient Runoff / Nitrate Leaching

Nutrients, such as nitrogen (N) and phosphorus, are prone to leaching when weather and soil conditions are right (Follett and Delgado, 2002). Cover crops can be used to not only lessen soil erosion, but also to reduce nutrient runoff. Meisinger and Ricigliano (2017) found that cereal cover crops in the Mid-Atlantic region of the United States lowered the total NO_3-N leaching by 50-95% compared to no cover in a corn-soybean rotation simulation. Another study found that cover crops from the Brassicaceae family were able to reduce nitrate leaching by 75% (Nouri et al., 2022). This reduction in leaching aids in stopping leached nitrogen from negatively impacting local and major waterways. Ultimately, lowering the amount of nitrate that is leaching out of a field benefits the following cash crop and helps enhance the water quality of water bodies in the area (Christianson et al., 2021). Moreover, phosphorus can also be impacted by the presence of cover crops (Aronsson et al., 2016). Having cover crops in the field can aid in preventing the loss of particle-bound phosphorus, especially in cold climatic regions of the United States (Liu et al., 2019). Research by Norberg and Aronsson (2020) found that the presence of cover crops had no impact on overall phosphorus leaching (Norberg and Aronsson, 2020). In the end, while cover crops can decrease overall nitrate leaching, they may increase the overall concentration of the nutrients within the runoff (Miller et al., 1994).

Cost Share/Subsidies/Costs for Farmers

The addition of cover crops into a cropping system results in a larger monetary expense and workload for farmers (Weil and Kremen, 2007). The implementation of cover crops has various direct and indirect costs associated with it such as seed costs, equipment, labor, fuel, etc.

(Bergtold et al., 2019). According to the United States Department of Agriculture (USDA), cover crop seed in 2015 costed anywhere from $39.51 to $259.26 per hectare, depending on the species (*Cover Crops for the Southeast: Cover Crop Costs.,* n.d.). Typically, legume species cost more than grass species (Snapp et al., 2005). Other production costs include potentially a loss in profit if cash crop yields are reduced (Calcante et al., 2022; Snapp et al., 2005). Schnitkey et al., (2016) found that in no-till systems, the additional herbicides would cost a farmer $12.35 USD extra per hectare of cover crop. This increased cost is a result of a higher labor need, potential need for different equipment, seed cost, fuel, and many other factors (Bergtold et al., 2019). Each additional cost for cover crops varies depending on the style of operation and program that they are being integrated into. For some farmers, these costs outweigh the benefits of the cover crops.

Cost share programs have been created to incentivize best management practices, including cover crop use, in Virginia to help protect the Chesapeake Bay and other watersheds. The Virginia Department of Conservation and Recreation states that for the 2025 fiscal year, 207 million dollars have been devoted to the Virginia Agricultural Best Management Practices Cost-Share Program (VACS) which provides funds for the use of various best management practices, including cover crops (*Agricultural Cost-Share 22-23 Program Overview*. (n.d.)).

Improving Soil Health

Cover crops are typically associated with more soil organisms. Thus, mixtures of diverse cover crops tend to lead to greater diversity of soil organisms (Vukicevich et al., 2016). As cover crops decompose their residues contribute to soil organic matter. Soil organic matter can improve a soil's buffering capacity, soil water capacity, nutrient cycling, and overall crop yields (Adetunji et al., 2020; Dabney et al., 2001). Leguminous cover crops specifically contribute to overall soil health by increasing plant available nitrogen via the nitrogen produced within their biomass

(*Cover Crop (Ac.) (340) Conservation Practice Standard*, n.d.). These legume cover crops can increase the soil's pH due to their nitrogen output increasing overall acidity which can lead to a larger availability of soil nutrients depending on the initial soil pH (Adetunji et al., 2020; Nyatsanga and Pierre, 1973; Vanzolini et al., 2017).

Creating Habitats for Beneficial Insects & Pests

Certain cover crop species can provide habitat and resources for beneficial insects. Pollinator communities have been found to utilize the floral resources provided by specific cover crops such as multiple species of clover (Bryan et al., 2021). These floral resources also aided in the abundance, richness, and overall conservation of the local bee community (Bryan et al., 2021). Natural enemies of major insect pests and predatory insects utilize cover crops as shelter. For example, Riechert and Bishop (1990) found that the addition of a grass hay mulch, with or without the addition of flowers, resulted in higher spider populations and lower amounts of pest damage. Similarly, other research found that cover crops integrated into fields prior to cotton being planted increased predatory insects in the following cotton crop (Tillman et al., 2004). However, cover crops in or around fields can also attract harmful pests and provide them shelter. Dunbar et al. (2016) found that having a cereal rye (*Secale cereale* L.) cover crop prior to corn can lead to higher amounts of injured corn and a greater abundance of true armyworm (*Mythimna unipuncta* H.). Similarly, Smith et al. (1988) found that a no till cereal rye cover crop can lead to higher amounts of bean leaf beetles (*Cerotoma trifurcata* F.) and Japanese beetles (*Popillia japonica* N.) compared to plots with no cereal rye, plots where the cereal rye was disked and plowed into the soil, plots where the cereal rye was only disked, and plots with cereal rye on top of the soil. Other research has had similar findings of major crop pests residing in cover crops and causing damage (Bryant et al., 2013; Costello and Altieri, 1995). For example,

cover crops have been found to be occasional hosts for slugs and rodents (Fronczak and Galbraith, 2023).

Soil Moisture Conservation/Reductions

Soil surface crust can restrict the amount of water that gets into soil which poses a problem for many crops (Folorunso et al., 1992). A moisture content too low for a crop typically reduces establishment, or yield, depending on the life stage of the crop (Champagne et al., 2019; Dabney et al., 2001). Cover crops help to prevent issues such as these by breaking up the soil, reducing evaporative losses, and increasing precipitation infiltration (Chen and Weil, 2011; Fageria et al., 2005; Unger and Vigil, 1998). Folorunso et al. (1992) found that hairy vetch (*Vicia villosa* R.) cover crops lowered the strength of the soil surface by 24-41% and increased the soil's total water uptake. Similarly, a study in Missouri found that a cereal rye, crimson clover (*Trifolium incarnatum* L.), and daikon radish (*Raphanus sativus* var. *longipinnatus*) cover crop mixture helped to keep moisture in the soil prior to termination (Mendis et al., 2022). Other research has also supported the idea that cover crops can help maintain or increase soil moisture levels prior to planting (Gabriel et al., 2021).

After termination, leaving the cover crop's residue on the soil surface can aid in the conservation of soil moisture. Peterson et al. (2025) states that the presence of cover crop residue after termination can increase soil moisture by reducing the overall evaporation of water. Cover crops also help to increase the amount of water infiltrating the soil by slowing the water movement across the soil's surface due to the residue presence (Peterson et al., 2025). Similarly, a 7-year trial consisting of a maize-soybean rotation followed by a winter cover crop of cereal rye found that the cereal rye not only conserved soil moisture but also improved the soil water

table (Basche et al., 2016). This study also found that cover crops can increase the water retention abilities of soil and ultimately increase the plant available water (Basche et al., 2016).

Cover crops can reduce soil moisture at cash crop planting if they are not terminated or terminated too late (Unger and Vigil, 1998). In semiarid regions or in non-irrigated areas, if cover crops are not terminated early enough, they can cause a water deficit which can reduce the yields of the following cash crop (Balkcom et al., 2016; Dabney et al., 2001; Krueger et al., 2011). This reduced soil moisture content can cause cash crop seeds to not germinate (Achakzai, 2009). Aside from decreased germination rates, lower soil moisture at planting can result in stunting, reduced crop yields, reduced nutrient availability, less tillering, and even total crop failure (Begna, 2020; Hemati et al., 2022; Iqbal, et al., 2020; Végh, 1991).

Immobilizing Nitrogen

Cover crop termination timing can impact soil nitrogen. Throughout the cover crop growing season, a cover crop absorbs macro- and micro-nutrients. Once the cover crop is terminated and begins decomposing, these nutrients are released from the cover crop residues (Jahanzad et al., 2016). Moreover, if non-legume species cover crops are allowed to mature later into the season, they will continue to use nitrogen and nutrients to produce biomass. This nutrient uptake can deplete nitrogen and other nutrients in the soil.

Typically when a cover crop residue has a high carbon to nitrogen (C:N) ratio, the nitrogen within its biomass may not be available when the future cash crop needs it. The higher a cover crop's C:N ratio is, the longer its biomass takes to decay and the higher likelihood nitrogen will become immobile (Kuo and Jellum, 2002; Kuo and Sainju, 1998; Lacey et al., 2020). For most plant residue, a C:N ratio of over 25 results in nutrient immobilization (Quinn et al., 2023). Grass cover crops, such as cereal rye, have a higher (>25:1) C:N ratio compared to legume cover

crops such as hairy vetch (Kuo and Jellum, 2002). N deficiency can lead to crop stunting or increased fertilizer needs. The extra nitrogen fertilizer need has the potential to inflate the farmer's overall cost of production for the crop.

Termination (Volunteer Plants / Regrowth)

There are various ways to terminate cover crops. Two common methods are chemical termination and mechanical termination. For chemical control, herbicides are sprayed on the cover crop while mechanical control consists of mowing, plowing, or crimping the cover crop (Kumar et al., 2023; Palhano et al., 2018; Wortman et al., 2013). For years, chemical applications have been a standard practice for conventional farmers to terminate their cover crop. In the past few decades, however, many farmers have begun exploring other means of terminating their cover crops such as mechanical methods. Various research studies have seen regrowth associated with mowing cover crops such as cereal rye, wheat (*Triticum* spp.), and hairy vetch (Creamer and Dabney, 2002; Wilkins and Bellinder, 1996). This regrowth can potentially cause problems, such reduced cash crop yield, reduced soil moisture, or the need for more tillage depending on the system (Denton et al., 2023; Keene et al., 2017). Regrowth of cover crops can also occur if there is incomplete chemical termination (Bruce and Kells, 1990).

Moreover, termination that is either incomplete or after the cover crop has set viable seed can result in both volunteer plants, plants that reappear without being planted, and cover crop persistence in the subsequent cash crop or the following year. Several cover crop species, such as hairy vetch and cereal rye, have been found to reappear in the field the following year due to incomplete termination (Keene et al., 2017). When cover crops germinate at inopportune times or are improperly terminated, they act as weeds and compete with the cash crop for crucial resources such as light, water, sunlight, and nutrients (Aarssen et al., 1986; Brainard et al., 2012).

This competition results in either a loss in yield or requires more herbicide applications to the field (Brainard et al., 2012; Curran et al., 2015; Hanson et al., 1993).

Nutrients / Nutrient Cycling

Cover crops also have an impact on the nutrients and nutrient cycling of the systems they are in. Many cover crops provide nutrients, such as nitrogen, to the soil as they grow or as their biomass decomposes (Fageria et al., 2005). Legume cover crops can be utilized to input nitrogen into the soil (Shennan, 1992). Because of this nitrogen production, farmers will oftentimes plant legume cover crops prior to cash crops heavily reliant on nitrogen (Dabney et al., 2010; Myers and Watts, 2015). For example, prior to corn, a hairy vetch cover crop can produce over 140 kg N ha^{-1} (Wittwer and can der Heijden, 2020). A cover crop's biomass accumulation and the climate it is grown in can increase its total nitrogen accumulation and the nitrogen's release after termination (Leuthold et al., 2021; Thapa et al., 2022).

Aside from legumes, other cover crops can impact nutrient cycling in ecosystems. For example, cover crops with tap roots can acquire nutrients from farther down in the soil profile that other crops would be unable to reach (Jahanzad et al., 2017). This relocation can make these nutrients more available to future shallow rooted plants (Jahanzad et al., 2017). For example, research by White and Weil (2011) found that forage radish can uptake soil phosphorus into its biomass and also increase the phosphorus content around the holes created by its tap root leaving phosphorus more readily available for future crops. Overall, cover crops can play an important role in integrating more nutrients into soils and scavenging for previously unreachable nutrients.

Weed Suppression

The use of cover crops for weed suppression has increased over the past few decades. Currently, cover crops of varying species have been shown to lessen overall weed pressure early in a cash crop's season. While living, cover crops compete against weeds for resources such as light, nutrients, space, and water which leads to reduced germination and weed growth (Bunchek et al., 2020; Osipitan et al., 2018). For all cover crops, biomass production is heavily influenced by growing degree days (GDD), seeding rate, seeding date, soil type, and when the cover is terminated (Mirsky et al., 2017; Parr et al., 2011; Teasdale et al., 2004). After termination, the biomass residue left by cover crops also works to suppress weeds by allelopathy or smothering them (Creamer et al., 1996; Teasdale, 1996). Using cover crops as a weed control strategy is most effective when targeting annual weeds early in the season because these weeds are early on in their lifecycle making them vulnerable (Bastiaans et al. 2008; Teasdale et al., 2007). An in-depth discussion of various aspects of cover crops for weed suppression is presented in the next section.

Mechanisms of Weed Suppression

During Winter Growth

The winter growth of cover crops can suppress weeds in multiple ways. The first is competition for resources. Cover crops can compete with weeds for light by producing a canopy early in the season, potentially reducing emergence of weed seedlings (Brust and Gerhards, 2014; Crennan and Smith, 2005). Water is another resource cover crops compete for that can lead to reduced weed densities (Rueda-Ayala et al., 2015). A cover crop that has good early establishment and a uniform stand has a higher likelihood of successfully competing with weeds

(Teasdale et al., 2007). By crowding the weeds, the lack of space makes the environment less adequate for their growth (Mennan et al., 2020; Teasdale et al., 1998). Cover crops can also compete with weed species for nutrients such as nitrogen (Blanco-Canqui et al., 2015). Typically, cover crops with a higher C:N ratio, such as cereal rye, immobilize nitrogen from within the soil by incorporating it into their biomass (Finney et al., 2016). Similar to its impact on cash crops, this immobilization can also reduce weed growth by causing a deficiency (Pittman et al., 2020).

Allelopathy is defined as "the harmful effect that one plant has on another plant due to chemicals it releases into the environment" (Willis, 2007). Allelopathic effects from cover crops are another weed suppressor. Allelopathic chemicals found to reduce weed pressure include allyl isothiocyanate, isoflavonoids, phenolic acids, fatty acids, scopoletin, hydroxamic acids, dhurrin, and sorgoleone (Weston, 1996). Sturm and Gerhards (2018) reported that radish (*Raphanus sativus* L.), buckwheat (*Fagopyrum esculentum* M.), and black oats (*Avena strigosa* S.) provided up to 28% allelopathic weed suppression. Cereal rye has also been found to exude allelopathic chemicals and successfully lessen weed abundance (Jabran et al., 2015; Schulz et al., 2013). Furthermore, research focusing on brassica allelopathy found that brown mustard (*Brassica juncea* (L.) Czern.) reduced the field's weed biomass by 80%. When the biomass was incorporated into the soil, however, it lowered redroot pigweed (*Amaranthus retroflexus* L.) growth by 71% (Ercoli and Pampana, 2005). These reductions in weed biomass have been seen in other studies across the United States in various cropping systems (Björkman et al, 2015; Mennan et al., 2020; Wang and Warncke, 2008).

After Cover Crop Termination

Once cover crops are terminated, their biomass residue can aid in physically hindering weed growth and potentially lower weed germination by making the environment less suitable for weeds and weed seedling development (Teasdale et al., 1998). For example, smaller seeded annual weed species typically need more light to grow and persist and, as a result, are more sensitive to cover crop residues shading them (Teasdale, 1996). The level of weed suppression declines as cover crop biomass breaks down over time (Pittman et al., 2020). Because of this, cover crop biomass typically results in the most weed suppression earlier in the season (Teasdale, 1996). Different cover crop monocultures or cover crop mixtures have varying levels of biomass. Therefore, they result in varying amounts of overall weed suppression (Pittman et al., 2020; Teasdale, 1996). Cover crops that have dense stands, such as hairy vetch or grass polycultures, create large amounts of residue and tend to better control weed populations (Bàrberi and Mazzoncini, 2001; Florence et al., 2019; MacLaren et al., 2019).

Cover crop biomass can also act as insulation for the soil, resulting in less soil temperature fluctuations and overall keeping the soil's temperature cooler (Dabney et al., 2001). For some weeds, soil fluctuations break their dormancy and initiate their growth (Benech-Arnold et al., 2000; Travlos et al., 2020). For example, common lambsquarters (*Chenopodium album* L.) seeds germinate when they are exposed to temperature fluctuations from 2.4 to 15 C (Murdoch et al., 1989). Similarly, germination increased for redroot pigweed, spiny amaranth (*Amaranthus spinosus* L.), and tall waterhemp (*Amaranthus tuberculatus* L.) seeds when subjected to alternating temperatures (Travlos et al., 2020). Therefore, a reduction in soil fluctuation may lead to less weed emergence.

Reducing Weed Pressure

The amount of cover crop biomass that is needed for adequate weed suppression varies based on the weeds being suppressed and the system it is in. For all cover crops, biomass production is heavily influenced by growing degree days (GDD), seeding rate, seeding date, soil type, and when the cover is terminated (Mirsky et al., 2017; Parr et al., 2011; Teasdale et al., 2004). In Virginia, one of the most problematic weeds farmers and researchers alike are looking at suppressing with cover crops is Palmer amaranth (*Amaranthus palmeri* (S.) Watson). According to a meta-analysis conducted by Kumar et al. (2024), the use of cover crops reduced *Amaranthus* spp. weed density by 58% in the early season, 48% in the mid-season, and 44% in the late season in temperate cropping systems. Another study found that weed densities, of various grass and broadleaf species, were reduced by an average of 44% when cover crops were present (Weisberger et al., 2023). The presence of cover crops can not only decrease weed densities but can reduce weed biomass by hindering their growth (Bhaskar et al., 2021). Research has shown that *Amaranthus* spp. weed biomass was reduced by 59%, 55%, and 3% in the early, mid-, and late growing season, respectively, due to cover crop residues (Kumar et al., 2024). To achieve reductions in weed biomass and weed densities, a minimum amount of cover crop biomass is needed. For 50% reductions in *Amaranthus* spp. weed density, 4079 kg ha^{-1} of cover crop biomass was needed (Kumar et al., 2024). However, a review conducted by Weisberger et al. (2023) stated that 6600 kg ha^{-1} of cover crop biomass was needed for a 50% reduction of weed density. Again, this analysis was looking at various broadleaf and grass weed species rather than only *Amaranthus* spp.. Similarly, a meta-analysis focusing on the Midwest region of the United States found that 5000 kg ha^{-1} was needed to reduce weed biomass by 75% (Nichols et al., 2020). Moreover, research conducted by Ryan et al. (2011) found that as cereal rye biomass increased, as did overall weed suppression. However, in the end, 15000 kg ha^{-1} of

cereal rye biomass was needed to completely suppress weeds in that environment (Ryan et al., 2011). Overall, regardless of the weed species within the system, cover crop biomass accumulation throughout the season is key in terms of reducing total weed biomass and density.

Aside from just the sheer amount of biomass that a cover crop accumulates over a season, the characteristics of that residue are important. One aspect of cover crop residue that is crucial to its weed suppression ability is its C:N ratio. Typically, a larger C:N ratio results in the residue staying in the field longer, ultimately hindering weed growth longer (Osipitan et al., 2019; Ruffo et al., 2004). Hill et al. (2016), for example, found that cover crops with higher C:N ratios resulted in better weed suppression around the R1 stage of soybean. Similarly, a study conducted by Pittman et al. (2020) determined that a cover crop's C:N ratio needed to be 16:1 to suppress redroot pigweed 6 weeks after termination. At 8 weeks after termination, that minimum C:N ratio increased to 20:1 (Pittman et al., 2020). Moreover, trends similar to this were seen when investigating large crabgrass (*Digitaria sanguinalis* (L.) Scop.) and pitted morningglory (*Ipomoea lacunosa* L.) (Pittman et al., 2020).

Cover Crops & Herbicides

While cover crops alone aid in lowering weed density in row crop systems, research has shown that they work best paired with a pre-emergent herbicide and/or post-emergent herbicide (Grint et al., 2022a; Kumari et al., 2024; Reddy et al., 2003). The pairing of herbicides and cover crops has shown to be especially useful when combating herbicide resistant weeds such as Palmer amaranth and horseweed (*Erigeron canadensis* L.) (Essman et al., 2020; Montgomery et al., 2018; Werle and Blanco-Canqui, 2017). Adequate amounts of cover crop biomass can result

in less herbicide inputs for a field. Trolove et al. (2017) found that integrating a winter cover crop into maize silage rotations can result in similar yields compared to plots sprayed with herbicides. A decrease in herbicide inputs in soybeans within a forage-grain rotation has also been observed when there is delayed termination of a cereal rye cover crop. This later termination allowed for an increase in the cereal rye's biomass, resulting in better management of common weeds such as horseweed (Ficks et al., 2023).

Grasses (Cereal Rye & Black Oat)

Grass cover crops do especially well at scavenging nitrogen, producing large quantities of biomass, and growing quickly compared to non-grass cover crop species (Bybee-Finley et al., 2022; Dabney et al., 2001; Snapp et al., 2005). Cereal rye is a cover crop species popular in many regions, especially in Virginia. This cover is frequently integrated into soybean, corn, cotton, and peanut cropping systems in the United States (DeLaune et al., 2019; Duiker and Curran, 2005; Price et al., 2020; Ruffo et al., 2004). Many farmers opt to plant cereal rye due to its biomass accumulation, weed suppression capabilities, early maturation, nitrogen scavenging ability, cold tolerance, and fast-growing root system (Brandi-Dohrn et al., 1997; Clark, 2008; Duiker and Curran, 2005). In terms of biomass accumulation, cereal rye can produce 1480 kg ha^{-1} to 8509 ± 613 kg ha^{-1} of biomass in a season (Grint et al., 2022b; Finney et al., 2016). This extensive biomass accumulation can aid in overall weed suppression and the addition of organic matter back into the soil.

Additionally, black oats serve as a useful grass cover crop, though they are not as popular as some of their counterparts. Black oats provide various benefits similar to other grass covers, including their erosion control via their thick root mass and weed suppression potential (Marquez

et al., 2022). However, their beneficial attributes like a low (less than 25:1) C:N ratio, allelopathic effect on both annual grasses and small-seeded broadleaf weeds, and quick growth make them useful in various cropping systems (Clark, 2008; Marquez et al., 2022; Quinn et al., 2023). Research found that black oats have a lower mineralization rate compared to cereal rye, meaning that they could be used as an effective cover crop while the nitrogen recommendations for the cash crop would change very little (Schomberg et al., 2006a).

Legume (Hairy Vetch)

Leguminous cover crops have been used for decades due to the benefits they provide. Common legume cover crops in the mid-Atlantic region of the United States include Australian winter peas (*Pisum sativum* L. subsp. *Arvense*), red clover (*Trifolium pratense* L.), crimson clover, and hairy vetch (Curran et al., 2018). Each of these covers produces nitrogen via the bacteria, rhizobia, that lives in nodules on their roots (Mathesius, 2022). Legumes have a mutualistic relationship with rhizobia that entails the bacteria producing nitrogen for the plant and the plant providing carbon for the bacteria (Mathesius, 2022). The nitrogen produced by the rhizobia is integrated into the biomass of the cover crop and eventually makes its way into the soil after cover crop termination and decomposition, where it will be available for the following cash crop (Adetunji et al., 2020; Curran et al., 2015). Leguminous cover crops typically have a lower C:N ratio resulting in faster decomposition of their biomass compared to cereal cover crops (Balkcom et al., 2016). This quick decay leads to nutrients being more rapidly available within the soil. This nitrogen fixing process can not only benefit the following cash crop but can also reduce the amount of nitrogen fertilizer needed later in the season (Fageria et al., 2005). For

example, Doran and Smith (1991) found that a hairy vetch and oats fall cover crop produced 172.6 kg N ha^{-1} which had a nitrogen fertilizer equivalence of 112.1 kg ha^{-1}.

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Effect of Cereal Rye Termination in Hairy Vetch + Cereal Rye Cover Crop Mixtures on Biomass Accumulation and Weed Suppression in Corn

Abstract

Virginia corn (*Zea mays* L.) farmers are using a hairy vetch (*Vicia villosa* R.) and cereal rye (*Secale cereale* L.) mixture as a winter cover crop where the cereal rye is selectively terminated in March. The remaining hairy vetch is terminated at corn planting (so-called "planting green"). This program has the potential to capitalize on Virginia's cover crop subsidies, improve winter hairy vetch survival, shrink fertilizer costs, mitigate N immobilization and planting concerns from cereal rye, and suppress weeds. Since in-depth research has not evaluated this system, the goal of this experiment was to determine if a hairy vetch and cereal rye mixture, where the cereal rye is selectively killed in March, performs better than a hairy vetch monoculture for biomass accumulation, weed suppression, and corn yield. Cover crop biomass from December and March indicated hairy vetch monocultures established and overwintered better than mixtures. At corn planting in mid-April, hairy vetch monocultures tended to have more hairy vetch biomass (2164 to 3123 kg ha^{-1}) compared to mixtures (1440 to 1986 kg ha^{-1}). Accordingly, hairy vetch monocultures typically accumulated greater N content (38.2 to 213 kg ha^{-1}) compared to mixtures (13.2 to 185 kg ha^{-1}). Weed densities were not influenced by cover crop for Palmer amaranth (*Amaranthus palmeri* S. Watson), common ragweed (*Ambrosia artemisiifolia* L.), morningglory (*Ipomoea* spp.), or large crabgrass (*Digitaria sanguinalis* L.) Scop.). However, for total weeds, contrast statements indicated no difference between hairy vetch in monoculture or mixture and that cover crop mixtures with selective termination of the cereal rye had greater weed density than those without selective termination. Corn yield did not show a difference between monocultures and mixtures. Ultimately, while the presence of cereal

rye did not increase hairy vetch biomass or N content, weed densities and corn yield were similar regardless of cover crop or herbicide program. Thus, Virginia farmers may be able to capitalize on state cover crop subsidies for cereal rye and mixtures while not risking hairy vetch biomass accumulation, N accumulation, or weed suppression with the use of this method.

Keywords: Palmer amaranth (*Amaranthus palmeri* S. Watson), nitrogen content, corn yield, weed density.

Introduction

A cover crop is a crop, typically, a legume, grass, or brassica, that is grown between cash crop seasons that covers the soil (Mutch and Martin, 1998; Quintarelli et al., 2022). Cover crops can provide both agronomic and environmental benefits such as adding nutrients into the soil, weed suppression, soil erosion prevention, and improve water infiltration (Chalise et al., 2019; Kaye and Quemada, 2017; Osipitan et al., 2019; Sharma et al., 2018). Nutrients provided back to the soil depending on the species. Leguminous species, such as clover species or hairy vetch, are known to supply nitrogen benefitting the subsequent cash crop (Yang et al., 2019). One study found that a hairy vetch (*Vicia villosa* R.) cover crop produced over 140 kg N ha^{-1} prior to a corn (*Zea mays*) cash crop (Wittwer and van der Heijden, 2020). A meta-analysis revealed that a hairy vetch cover crop resulted in a corn yield increase of 17% without other nitrogen fertilization (Rodriguez et al., 2023). Additionally, cover crop surface biomass can suppress weeds within various cropping systems. For example, cover crop use was found to reduce *Amaranthus* spp. by up to 58% in the early season (Kumar et al., 2025). Regardless of species, cover crops with significant biomass production (~4100kg ha^{-1} to 6600 kg ha^{-1}) have been found to effectively

reduce weed pressure in various cropping systems (Kumar et al., 2025; Osipitan et al., 2019; Weisberger et al., 2023).

In agreement with the scientific literature, a majority of farmers planted cover crops with the goal of improving their soil health, adding soil organic matter to the soil, improving water filtration, and reducing soil erosion (*National Cover Crop Survey Report 2022-2023*, 2023). Farmers also mentioned that they were incentivized to use cover crops because of subsidies (*National Cover Crop Survey Report 2022-2023*, 2023). Similarly, the United States Department of Agriculture's (USDA) Economic Research Service, financial compensation via Federal, State, and private organizations are one of the factors resulting in higher cover crop adoption rates (Wallander et al., 2021). For these reasons, roughly 80% of farmers in the United States are utilizing cover crops, according to the National Cover Crop Survey Report 2022-2023. Moreover, between the years of 2017 and 2022, cover crop hectarage in Virginia increased from 165869 ha to 177560 ha between 2017 and 2022 (*Land Use Practices: 2022 and 2017*, 2024).

Cereal rye (*Secale cereale*) is commonly used in Virginia because of its ability to produce large amounts of biomass (>8000 kg ha^{-1} in some cases), scavenge nutrients, and reduce erosion (Camargo and Bagavathiannan, 2023). Legume species, like hairy vetch, are typically used because of their ability to provide nitrogen and potentially reduce fertilizer costs (Abdalla et al., 2019; Wittwer and van der Heijden, 2020). Virginia farmers use cereal rye partially due to the subsidies available by the federal and state governments, such as the Virginia Agricultural Best Management Practices (BMP) Cost-Share Program, which provide a higher payment for cereal rye than other grasses (*Agricultural BMP Cost Share Program*, n.d.).

Aside from their monetary and environmental benefits, cereal rye and hairy vetch also have drawbacks that can negatively impact farmers. Cereal rye, if left to mature, can result in

nitrogen immobilization due to its high (>25:1) carbon to nitrogen ratio (Doran and Smith, 1991; Glaze-Corcoran et al., 2023). This immobilization decreases the amount of nitrogen available for the following cash crop which can lower yields in nitrogen needy cash crops like corn (Duiker and Curran, 2005). The large amounts of biomass produced from cereal rye can reduce the cash crop's establishment (Wallace et al., 2023). Many farmers have also hesitated to implement cover crops in general because they are concerned about their equipment and/or about having yield reductions in their upcoming cash crop (*National Cover Crop Survey Report March 2025,* 2025). Hairy vetch also does little for erosion control during the fall due to its slow winter growth (Lawson et al., 2015). Moreover, hairy vetch's nitrogen production peaks around full bloom, which is not always at the time of corn planting in Virginia (Goldy and Wendzel, 2014). Due to this, farmers are unable to capitalize on the cover crop's highest amount of available nitrogen.

To take full advantage of benefits while mitigating drawbacks such as nitrogen immobilization and planting issues associated with cereal rye, progressive corn farmers in Virginia have started to implement a new strategy, so called- "the Gluten-Free Method." Paul Davis is a farmer from New Kent, Virginia who first created and implemented this method on his family's farm, Davis Produce. The Gluten-Free Method consists of simultaneously planting cereal rye and hairy vetch together in mid-Fall. The cover crop is allowed to grow throughout the winter until mid-March. At mid-March, the farmer sprays the cover crop with clethodim in order to selectively terminate the cereal rye. The hairy vetch is left to continue to grow and accumulate biomass and nitrogen until mid- to late-April. At this time, the hairy vetch is roller-crimped to flatten it, its biomass planted through, and finally sprayed (typically with a dicamba and glyphosate mixture) to terminate it all the same day. This method is growing in popularity in

Virginia. Adopting farmers report several observations including fall nutrient scavenging, overwintering of the hairy vetch, weed suppression, erosion control, and a reduction in nitrogen fertilizer need due to the hairy vetch's nitrogen production (Brainard et al., 2012; Thapa et al., 2018; Ma et al., 2025).

While literature supports farmer-observed benefits, the system has not been scientifically scrutinized as a whole. Therefore, the goal of this research is to evaluate the Gluten-Free Method and quantify its ability to reduce weed density, determine if the hairy vetch overwinters better with the addition of cereal rye, and determine potential nitrogen contributions from the hairy vetch.

Materials and Methods

Study Sites.

To evaluate and compare the weed suppression effectiveness of hairy vetch (*Vicia villosa* R.) + cereal rye (*Secale cereale* L.) mixtures or hairy vetch in monoculture, the experiment was conducted at two locations in two seasons for a total of four site-years. Studies were initiated in the fall of 2023 and 2024 at Kentland Farm near Blacksburg, VA, USA (37°11'37"N 80°34'21"W) and near Blackstone, VA, USA at the Southern Piedmont Agricultural Research and Extension Center (37°05'00"N 77°58'15"W). The Kentland Farm location is within the New River's flood plain and has a Ross soil with a taxonomic class is fine-loamy, mixed, superactive, mesic Cumulic Hapludolls. The soil in Blackstone is an Applying coarse sandy loam and its taxonomic class is fine, kaolinitic, thermic, Typic Kanhapludults (*Web Soil Survey*, 2019). The Kentland Farm locations in 2023 and 2024 were previously in fallow and corn (*Zea mays*), respectively. In 2023, the field was prepared for cover crop planting by paraquat (Gramoxone®

SL 2.0; Syngenta Crop Protection, Greensboro, NC, USA) applied at 841 g ai ha^{-1} + 1% v v^{-1} crop oil concentrate, then disked, and finally cultipacked. The following year, the field was prepared by disking twice and then cultipacked. In 2023, the Blackstone location was previously in corn. Prior to cover crop planting, the field was cut to around 10 cm with a rotary mower and tilled with a disk twice. At planting, the field was sprayed with a mixture of glyphosate (Roundup Powermax 3; Bayer Crop Science, Creve Coeur, MO, USA) at 1,262 g ae ha^{-1} and glufosinate (Liberty 280 SL; BASF, Florham Park, NJ, USA) at 788 g ai ha^{-1}. In 2024, the field was cut to roughly 10 cm using a tractor mounted rotary mower, tilled using a disk, and sprayed with a mixture of glyphosate and glusfosinate after being fallow the prior season.

Treatments and Experimental Design.

The objective was evaluated using a factorial treatment structure. Cover crop was the first factor and had (1) Patagonia hairy vetch monoculture, (2) Patagonia hairy vetch with cereal rye, (3) MT hairy vetch monoculture, and (4) MT hairy vetch with cereal rye. MT hairy vetch is a later maturing variety while Patagonia hairy vetch is an earlier maturing variety. These two varieties were selected to represent the full range of maturing rates of hairy vetch planted in Virginia. The cereal rye variety used was Late Abruzzi, which is commonly used in the region. Cereal rye termination cocktail was the other factor and was either (A) no selective herbicide termination to provide a hairy vetch + cereal rye mixture comparison treatment, (B) 140 g ai ha^{-1} of clethodim (Select Max; Valent USA LLC., San Ramon, CA, USA) in 50/50 water/28% nitrogen, (C) 140 g ai ha^{-1} of clethodim in water with non-ionic surfactant at 0.25% v v^{-1}. The additional nitrogen within the clethodim application was included to determine if it would benefit the biomass production of the hairy vetch, as reported by farmers. Herbicide applications were made using a 3 m boom attached to a CO_2 backpack sprayer that was equipped with six

TeeJet XR110015 (Teejet Technologies, Glendale Heights, IL, USA) nozzles or with an all-terrain vehicle that was set up with a 3.7 m boom equipped with seven like nozzles. These setups were calibrated to deliver 140 L ha^{-1} of mixture at 207 kPA at 4.83 km h^{-1}. Plots were at least 7.6 m by 3.0 m and arranged in a randomized strip block design with four replications at each site. Cover crop planting occurred on October 4th 2023 and October 11th 2024 in Blackstone and on October 13th 2023 and October 18th 2024 in Blacksburg. Hairy vetch varieties and cereal rye were drilled to a depth of roughly 2.5 cm deep both years with a seed drill. In 2023, both hairy vetch species at the Blackstone location were unintentionally planted at a rate of around 91 kg ha^{-1}, however statistical analysis indicated no differences in results when compared to other site years. All other site-years were planted at roughly 22 kg ha^{-1}. All site years were seeded at 84 kg cereal rye ha^{-1}.

Crop Production Practices

A mixture of glyphosate at 1262 g ae ha^{-1} and dicamba at 407 g ae ha^{-1} (Xtendimax; Bayer Crop Science, St. Louis, MO, USA) was applied to the field to terminate the cover crop after they were roller-crimped. Directly following the terminating herbicide application, corn, variety DKC110-10RIB (Dekalb with Acceleron Seed Treatment; Bayer Crop Science, St. Louis, MO, USA) was planted at both locations both years. In both the spring of 2024 and the spring of 2025, the corn was planted on April 16th and April 23rd in Blackstone and Blacksburg, respectively. Each year, the corn was planted at a population of 72376 seeds per hectare with 76.2 cm row spacing and fertilized with 67 kg N ha^{-1} applied as 19-19-19 the same day. The corn was not irrigated either year. A month later, Halex GT (Syngenta Crop Protection, Greensboro, NC, USA) (*S*-metolachlor at 1055 g ai ha^{-1} + glyphosate at 1055 g ae ha^{-1}+ mesotrione at 106 g ai ha^{-1}) was sprayed as a post emergent herbicide and granular urea was applied at 129 kg N ha^{-1}.

Both years, the corn in Blackstone was top-dressed with 129 kg N ha^{-1} of 34-0-0-8 while the corn in Blacksburg received 183 kg N ha^{-1} of 46-0-0. In Blackstone in 2024, elemental sulfur (90%) was spread at 28 kg ha^{-1} to combat a sulfur deficiency roughly six weeks after corn planting.

Data Collection

Hairy vetch biomass samples were collected from each plot in December followed by 1 month prior to, and at, corn planting/cover crop termination. These timings were chosen in order to compare hairy vetch establishment, overwintering, and final biomass among treatments, respectively. Samples were taken from each plot using a randomly placed 0.25 m^2 quadrat, dried until a constant weight, and weighed. A homogenized subsample was subjected to nutrient analysis to determine the carbon and nitrogen contents of the samples using near-infrared (NIR) spectroscopy.

Weed suppression data were collected 1 month after corn planting, just prior to the postemergence herbicide application. Within two randomly placed 0.5 m^2 quadrats in each plot, the three most abundant weeds were counted and all other weeds present counted collectively as "others." Palmer amaranth (*Amaranthus palmeri* S. Watson) was among the top three weeds in all site-years. Species counted are listed in Table 1.1.

At the end of both seasons, corn from each plot was harvested with a Wintersteiger (Wintersteiger Inc., Salt Lake City, UT, USA) plot combine from the middle two rows by at least 6 m of row in each plot. Grain yield data were adjusted to 15.5% moisture. Plots were harvested on September 10th and October 29th, 2024, in Blackstone and Blacksburg, respectively. The following year, corn was harvested in Blackstone on September 23rd and in Blacksburg on October 3rd.

Data Analyses

The biomass, weed suppression, nutrient content, and yield data were analyzed in JMP Pro 18 (SAS Institute, Inc., Cary, NC, USA). All data were subjected to analysis of variance (ANOVA). For December and 1 month prior to planting, cover crop was a fixed effect. For all other data, herbicide program, cover crop, and their interaction were fixed effects. Both location and replication nested within location were treated as random variables. When ANOVA was significant, a subsequent means separation was performed using a Student's T test ($p \leq 0.05$) to compare significant treatment effects. In some cases, contrast statements ($p \leq 0.05$) were conducted to best answer experimental objectives. All data sets were transformed to the best of our abilities to meet a normal distribution prior to analysis. Data sets that were unable to meet a normal distribution were analyzed using untransformed data.

Results and Discussion

Cover Crop Biomass Accumulation

For biomass accumulation, both December and 1 month prior to corn planting, cover crop was a significant factor ($p < 0.001$). At both times, the monocultures produced more hairy vetch biomass compared to the mixtures (Figures 1.1 and 1.2). Patagonia hairy vetch alone was in the top statistical grouping at both times. Mixtures of cereal rye and hairy vetch were always in the least two performing statistical groupings for hairy vetch biomass production. At corn planting, the interaction between cover crop and herbicide program was significant ($p < 0.001$; Figure 1.3). Contrast statements revealed that hairy vetch monocultures produced 827 kg ha^{-1} ($p < 0.001$) more hairy vetch biomass than the mixtures (Figure 1.3). When cereal rye was selectively terminated, monocultures still produced 560 kg ha^{-1} more hairy vetch biomass ($p<0.001$). Lastly, to determine whether the adjuvant/nitrogen solution with clethodim mattered in terms of hairy

vetch biomass, a contrast statement comparing the two herbicide programs that selectively terminated the cereal rye demonstrated that there was not a difference within mixtures ($p = 0.31$) or monocultures ($p = 0.31$).

Previous research shows that cereal rye present in a mixture can lessen the winter kill of hairy vetch in cold climates (Brainard et al., 2012; Jannink et al., 1997). For example, Brainard et al. (2012) found the presence of cereal rye resulted in 100% hairy vetch winter survival compared to 75% without in Michigan. Our results showed no difference in overwintering as measured at the March sampling timing. This differs from prior research likely because typical Virginia winters lack large durations of cold or extremely cold temperatures that could show differences amongst the cover crops. Without snow cover, hairy vetch begins to winter kill at -15 degrees Celsius (Clark, 2008). In the winters of 2023-24 and 2024-25, the temperature did not drop below a daily average of –2.6 and –9.1 degrees Celsius at either location, respectively (*WeatherSTEM Data Mining*). Therefore, the winter temperatures these years did not drop low enough to truly show the impact of the cereal rye on the hairy vetch's overwintering. Hairy vetch biomass data from corn planting demonstrates that Virginia farmers who are looking to maximize their hairy vetch biomass should plant monocultures. Our research, similar to previous research, demonstrated that cereal rye within the cover crop mixtures will dominate in terms of biomass production (Ruffo and Bollero, 2003; Brainard et al., 2012). We also saw reduced hairy vetch biomass within these mixtures at corn planting, likely due to competition between the hairy vetch and cereal rye. While soil erosion and fall nutrient scavenging were not measured in this experiment, these may be of value to the farmer and thus worth considering when choosing to plant hairy vetch alone or with cereal rye.

Hairy Vetch Nitrogen Content at Corn Planting

The interaction between cover crop and herbicide program was significant ($p = 0.007$) for the amount of nitrogen in the hairy vetch at corn planting (Figure 1.4). Due to this interaction, contrast statements were conducted to answer experimental objectives (Figure 1.4). The first contrast statement revealed that hairy vetch monocultures produced significantly more nitrogen (~31 kg ha^{-1}) compared to the treatments that contained cereal rye ($p < 0.001$). The second contrast demonstrated that there was roughly 21 kg ha^{-1} of nitrogen difference ($P < 0.001$) between the mixtures and monocultures when cereal rye was selectively terminated. Finally, the results of the third contrast looking at the impact of the adjuvant/nitrogen solution within clethodim containing treatments showed no difference between just the treatments containing cereal rye ($p = 0.113$), just the hairy vetch monocultures ($p = 0.966$), and the hairy vetch monocultures compared to the mixtures ($p = 0.275$).

These results demonstrate that Virginia farmers who chose to implement hairy vetch monocultures rather than cereal rye and hairy vetch mixtures will see higher amounts of nitrogen potentially available for their following corn cash crop. Past research has found that, while hairy vetch alone cannot contribute enough nitrogen to sustain a nitrogen needy cash crop, it can be used to reduce the amount of nitrogen fertilizer needed (Doran and Smith, 1991; Pott et al., 2021; Utomo et al., 1990). A study conducted by Pott et al. (2021) found that hairy vetch alone was found to have a nitrogen fertilizer replacement value of 45 to 151 kg N ha^{-1} depending on the type of yield environment. The biomass needed to achieve this amount of fertilizer equivalent ranged from 4234 to 5834 kg ha^{-1} and had a nitrogen content of 188 to 212 kg ha^{-1} (Pott et al., 2021). Compared to Pott et al.'s (2021) study, the hairy vetch biomass data and nitrogen content from most of this experiment's treatments were lower. Around 70% of samples contained less than 100 kg N ha^{-1} and 76% had less than 3000 kg ha^{-1} of hairy vetch biomass. Our samples had

nitrogen contents that ranged from 13.2 to 213 kg N ha^{-1}. Regardless, these contributions would provide enough nitrogen to lower overall nitrogen fertilizer need and ultimately save farmers money when it came to purchasing their fertilizer (La Menza et al., 2025).

Weed Density Data

Analysis was only conducted on weeds that were present for at least two site years. Thus, the weed data analyzed included Palmer amaranth, morningglory species, common ragweed, and large crabgrass which were present 4, 2, 2, and 2 site years, respectively. Other weeds and total weeds were also included. For Palmer amaranth, common ragweed, and large crabgrass, no factors within the final model were significant indicating regardless of cover crop or herbicide program, weed densities were similar amongst treatments. Herbicide programs that selectively terminated cereal rye had significantly ($p = 0.029$) greater morningglory density present compared to no selective termination (Figure 1.5). Cover crop was a significant ($p = 0.004$) factor for other weeds in the study. The two hairy vetch monocultures had greater weed density compared to the cereal rye and Patagonia hairy vetch mixture. The cereal rye and MT hairy vetch mixture was statistically not different from all other cover crops (Figure 1.6). The interaction between herbicide program and cover crop was significant for total weeds (Figure 1.7). To better dissect the results from the interaction, five contrast statements were conducted on these data (Figure 1.7). The first stated that there were no differences between the monocultures and mixtures for total weed suppression ($p = 1.00$). The second statement was conducted among cover crop mixtures and compared the herbicide programs that resulted in selective termination of the cereal rye and the one that did not. The results of this contrast statement indicated that the mixtures where the cereal rye was terminated had 0.54 more weeds m^{-2} compared to control treatments ($p < 0.001$). Other contrast statements compared herbicide programs where cereal rye

was selectively terminated and demonstrated that regardless of the adjuvant/nitrogen with clethodim, there was no difference in total weed density ($p = 0.36$).

Hairy vetch + cereal rye mixtures tend to suppress various species of weeds more effectively than hairy vetch monocultures (Burgos and Talbert, 1996; Lawson et al., 2015; Mirsky et al., 2011). Burgos and Talbert (1996) found that cereal rye and hairy vetch mixtures contained at least 50% less weeds compared to a hairy vetch monoculture or no cover crop. This experiment's results differ from these studies because all weed data aside from other weeds and total weeds demonstrates that both hairy vetch monocultures and hairy vetch + cereal rye mixtures where the cereal rye is selectively terminated resulted in similar weed densities. These results may be due to cereal rye being terminated before it accumulated sufficient biomass for weed suppression or the hairy vetch inputting nitrogen into the soil resulting in weed growth. The results focusing on other weeds present showed that cover crop was significant and, on average, the hairy vetch monoculture plots had significantly more other weeds compared to the mixtures. Moreover, total weed data demonstrated similar results to the individual weed species further supporting the claim that hairy vetch monocultures suppress weeds equally, if not better, than hairy vetch + cereal rye mixtures when the cereal rye is selectively terminated in mid-March.

Yield

Cover crop was the only significant factor ($p = 0.017$) for corn yield. The Patagonia hairy vetch + cereal rye mixture was not different from all other treatments (Figure 1.8). The Patagonia hairy vetch monoculture and the cereal rye and MT hairy vetch mixture had higher yields than the MT hairy vetch monoculture. The average yields ranged from 8162 to 9050 kg ha^{-1}. These

yields are comparable to the average Virginia corn yields of 10491, 9863, and 7162 kg ha^{-1}, in 2022, 2023, and 2024, respectively.

Previous research has found that cover crops do not always increase cash crop yields. For example, a review conducted by Abdalla et al. (2019) found that the use of cover crops decreased yields by ~4% compared to the control treatment. However, other research shows that there is a positive correlation between the use of cover crops, specifically legume species, and increased corn yields (Chahal and Van Eerd, 2023). In the past, the incorporation of hairy vetch as a cover crop into a crop rotation increased corn grain yield compared to no cover crop and an oat (*Avena sativa* L.) + radish (*Raphanus sativus* L.) cover crop by 14% and 12%, respectively (Singh et al., 2020). The results of our study demonstrate that regardless of cover crop, the yields were similar. This may have been due to insufficient amounts of hairy vetch biomass and thus reduced nitrogen inputs. Regardless, these results indicate that farmers, when deciding whether to utilize a hairy vetch monoculture or hairy vetch + cereal rye mixture, should consider other known benefits of the cover crops rather the yield initially.

Tables

Table 1.1 Weed species counted at either location during the 2024 and 2025 seasons in Virginia field experiments.

Category	**Location & Year**			
	Blacksburg 2024	Blackstone 2024	Blacksburg 2025	Blackstone 2025
Most Abundant Weed Species	Palmer amaranth (*Amaranthus palmeri* S. Watson)	Palmer amaranth	Palmer amaranth	Palmer amaranth
Second Most Abundant Weed Species	Morningglory species (*Ipomoea hederacea* J. & *Ipomoea lacunosa* L.)	Large crabgrass (*Digitaria sanguinalis* (L.) Scop)	Morningglory species	Giant foxtail (*Setaria faberi* H.)
Third Most Abundant Weed Species	Common ragweed (*Ambrosia artemisiifolia* L.)	Common ragweed	Yellow nutsedge (*Cyperus esculentus* L.)	Large crabgrass
Other Weed Species Present	Common lambsquarters (*Chenopodium album* L.), Large crabgrass, Johnsongrass (*Sorghum halepense* (L.) Pers.)	Giant foxtail, Pokeweed (*Phytolacca americana*), Pitted morningglory, and Tropic croton (*Croton glandulosus* var. *septentrionalis* Müll. Arg.)	Pokeweed (*Phytolacca americana* L.), common lambsquarters, and goosegrass (*Eleusine indica* (L.) Gaertn.)	Pokeweed, common ragweed, and goosegrass

Figures

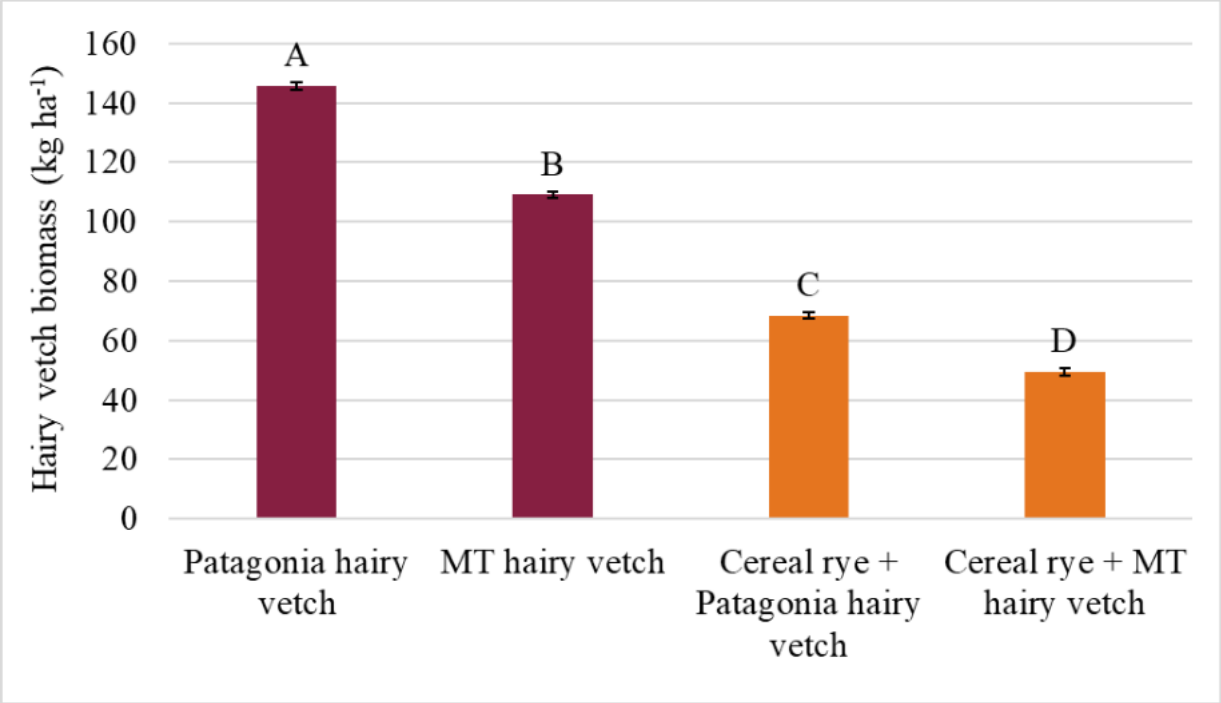


Figure 1.1. December hairy vetch biomass accumulation LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate hairy vetch and cereal rye mixtures while maroon bars indicate hairy vetch monocultures.

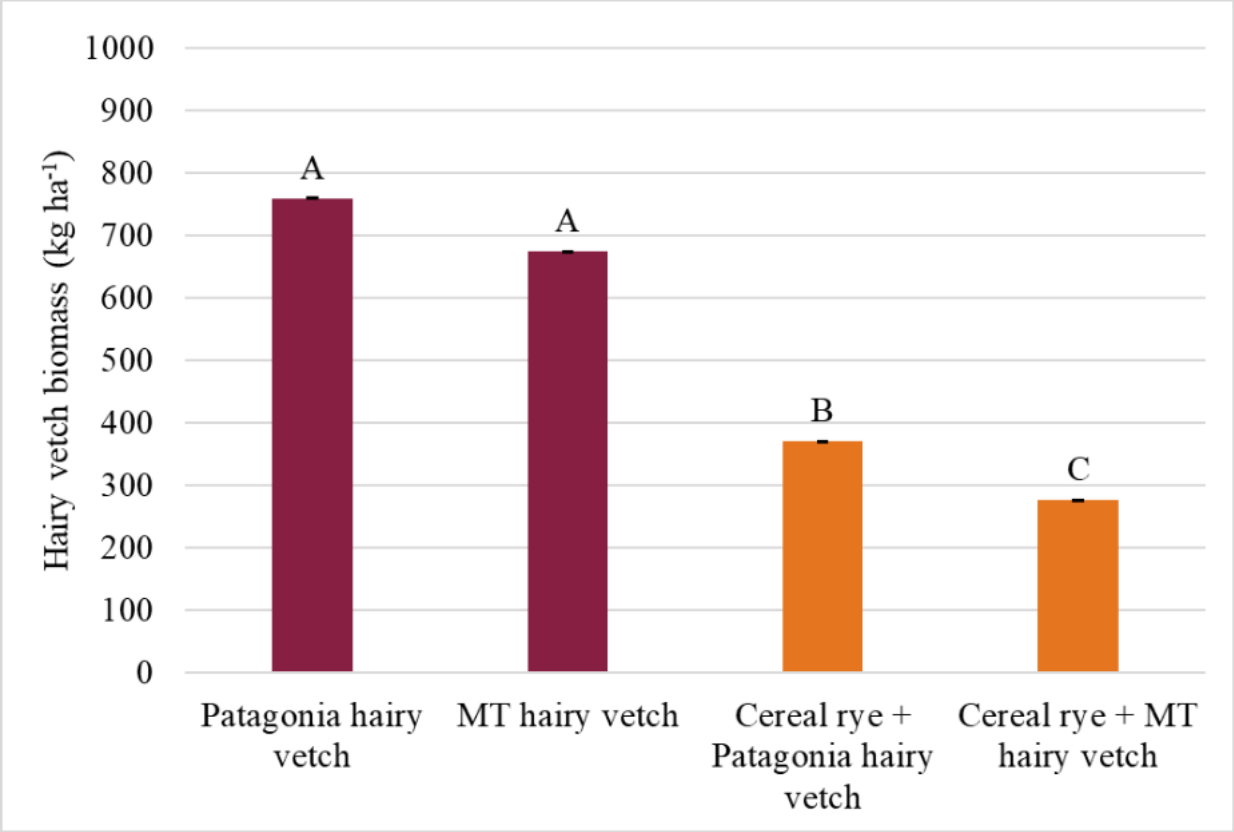
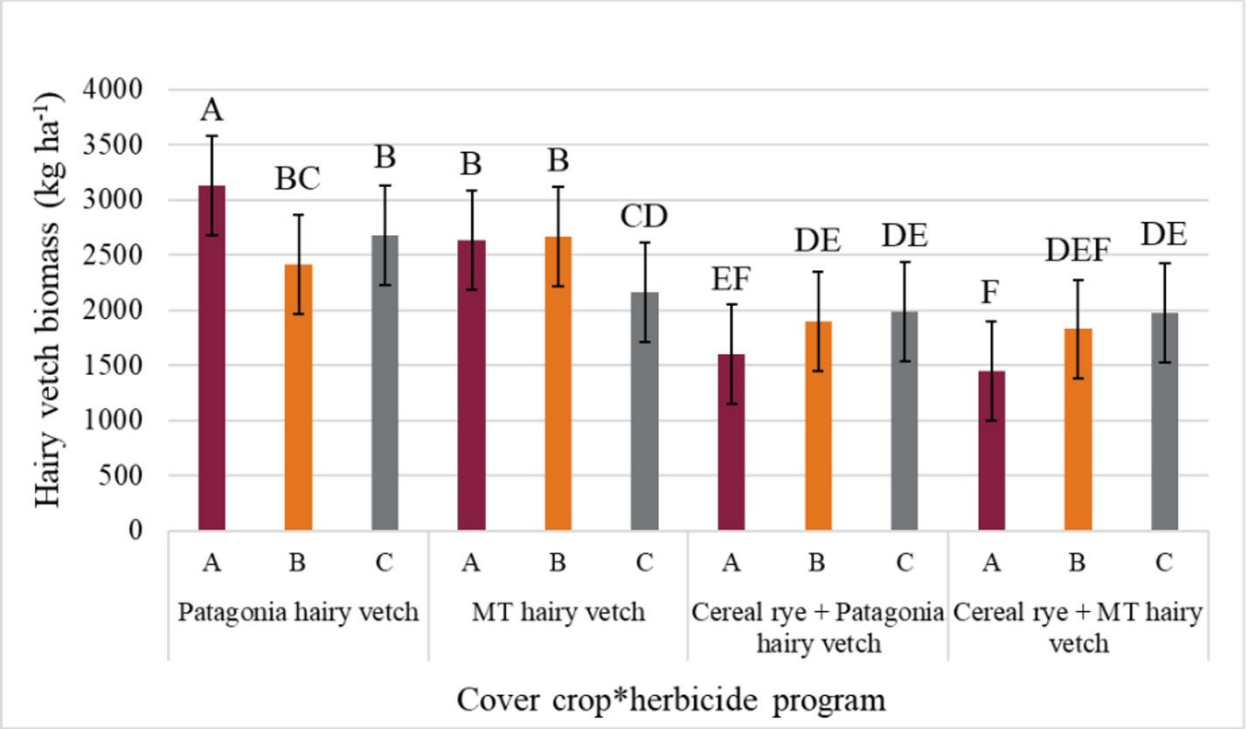
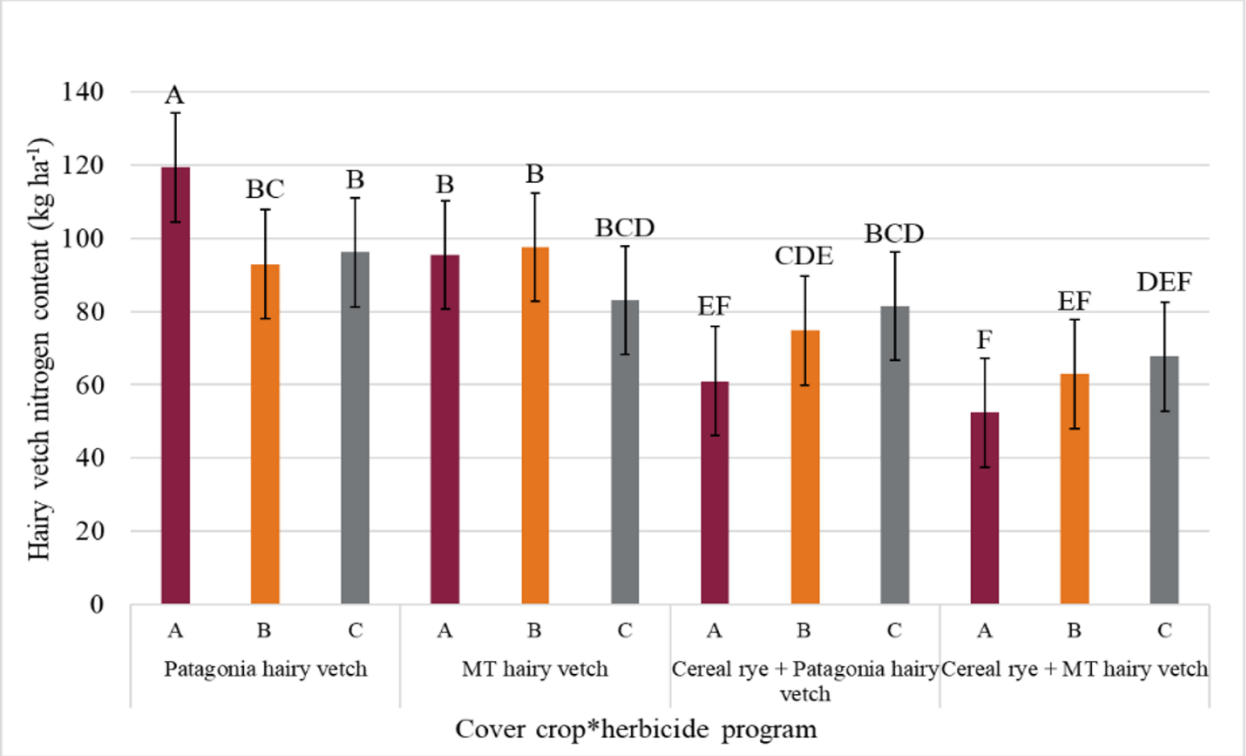


Figure 1.2. 1 month prior to corn planting hairy vetch biomass accumulation LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate hairy vetch and cereal rye mixtures while maroon bars indicate hairy vetch monocultures.



Contrasts	Difference in Hairy Vetch Biomass	P value
	kg ha^{-1}	
Hairy vetch monocultures vs. hairy vetch + cereal rye mixtures	827	**< 0.001**
Monocultures with herbicide treatments B and C vs. mixtures with herbicide treatments B and C	560	**< 0.001**
Herbicide treatment B vs. herbicide treatment C	0	1.00
Mixtures with herbicide treatment B vs. mixtures with herbicide treatment C	-120	0.306
Monocultures with herbicide treatment B vs. monocultures with herbicide treatment C	120	0.306

Figure 1.3. At corn planting hairy vetch biomass LS means (with SE bars) for the interaction between cover crop and herbicide program and contrast statements from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Maroon bars indicate herbicide program A (no selective cereal rye termination), orange bars indicate herbicide program B (selective cereal rye termination clethodim (Select Max; Valent USA LLC., San Ramon, CA, USA) in 50/50 water/28% UAN), and grey bars indicate herbicide program C (selective cereal rye termination with clethodim in water with non-ionic surfactant 0.25% v v^{-1}).



Contrasts	Difference in Hairy Vetch Nitrogen Content	P value
	kg ha^{-1}	
Hairy vetch monocultures vs. hairy vetch + cereal rye mixtures	30.7	**< 0.001**
Monocultures with herbicide treatments B and C vs mixtures with herbicide treatments B and C	20.7	**< 0.001**
Herbicide treatment B vs herbicide treatment C	-5.4	0.275
Mixtures with herbicide treatment B vs mixtures with herbicide treatment C	-11.0	0.113
Monocultures with herbicide treatment B vs monocultures with herbicide treatment C	0.30	0.966

Figure 1.4. At corn planting hairy vetch nitrogen content LS means (with SE bars) for the interaction between cover crop and herbicide program and contrast statements from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Maroon bars indicate herbicide program A (no selective cereal rye termination), orange bars indicate herbicide program B (selective cereal rye termination clethodim (Select Max; Valent USA LLC., San Ramon, CA, USA) in 50/50 water/28% UAN), and grey bars indicate herbicide program C (selective cereal rye termination with clethodim in water with non-ionic surfactant 0.25% v v^{-1}).

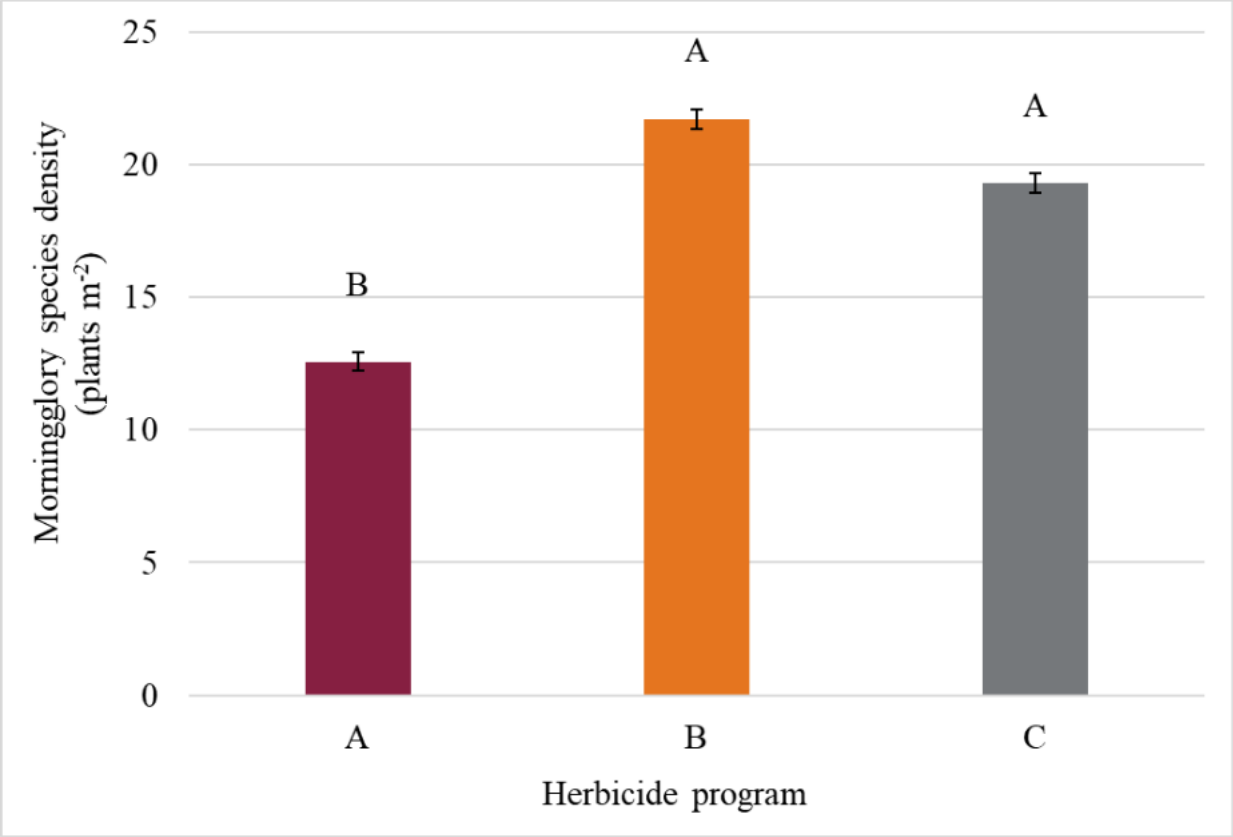


Figure 1.5. 1 month after corn planting morningglory species (ivyleaf and pitted morningglory) LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bar indicates herbicide program A (no selective cereal rye termination), the orange bar indicates herbicide program B (selective cereal rye termination clethodim in 50/50 water/28% UAN), and the grey bar indicates herbicide program C (selective cereal rye termination with clethodim in water with non-ionic surfactant 0.25% v v^{-1}).

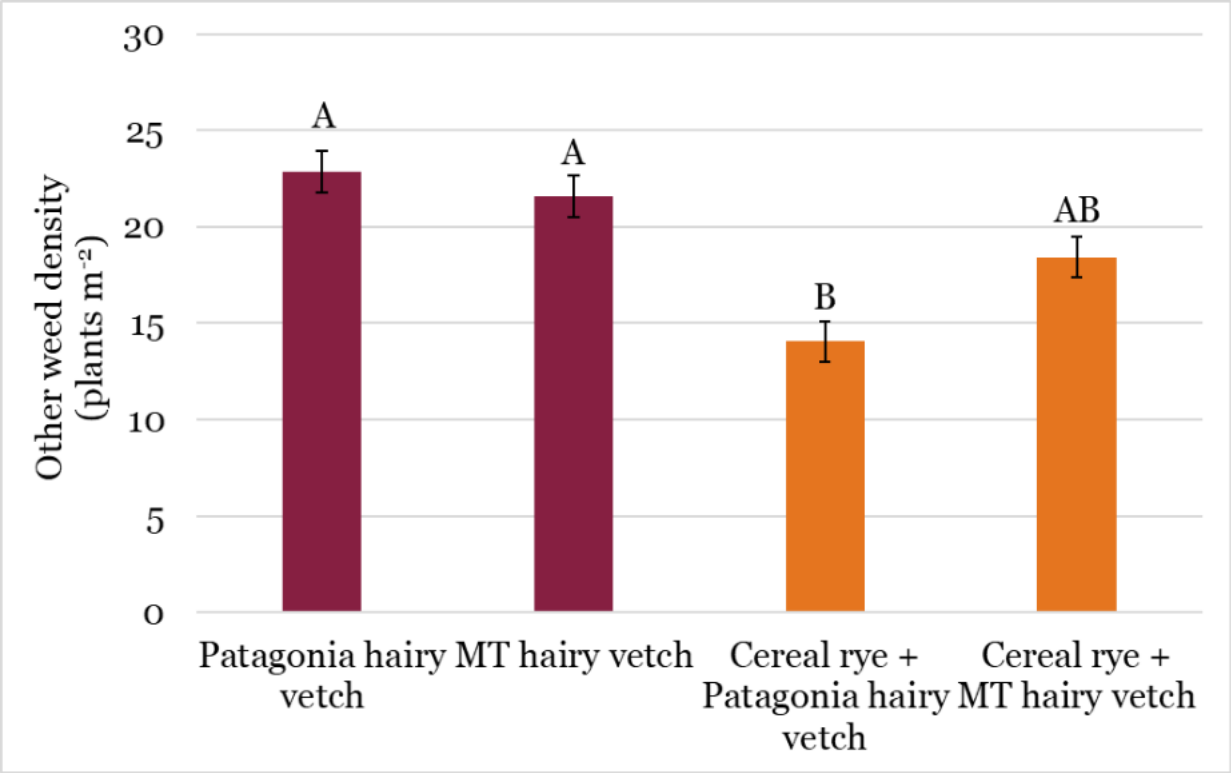
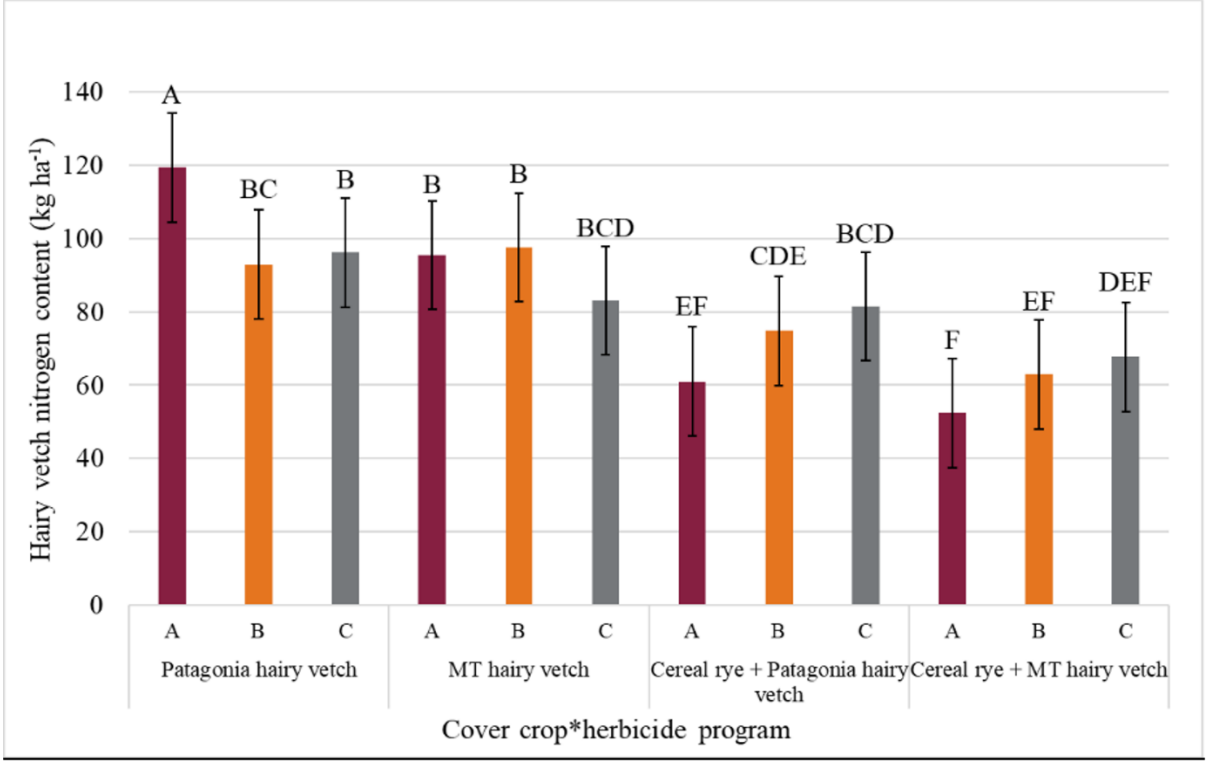


Figure 1.6. Other weed LS means (with SE bars) 1 month after corn planting from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate hairy vetch and cereal rye mixtures while maroon bars indicate hairy vetch monocultures.



Contrasts	Difference in Total Weed Densities	P value
	Plants m^{-2}	
Hairy vetch monocultures vs. hairy vetch + cereal rye mixtures	0.00	1.00
Control vs selectively terminated treatments	0.54	**< 0.001**
Herbicide treatment B vs. herbicide treatment C	0.07	0.36
Mixtures with herbicide treatment B vs. mixtures with herbicide treatment C	0.09	0.37
Monocultures with herbicide treatment B vs. monocultures with herbicide treatment C	0.04	0.68

Figure 1.7. Total weed LS means (with SE bars) 1 month after corn planting for the interaction between cover crop and herbicide program and contrast staetments from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Maroon bars indicate herbicide program A (no selective cereal rye termination), orange bars indicate herbicide program B (selective cereal rye termination clethodim (Select Max; Valent USA LLC., San Ramon, CA, USA) in 50/50 water/28% UAN), and grey bars indicate herbicide program C (selective cereal rye termination with clethodim in water with non-ionic surfactant at 0.25% v v^{-1}).

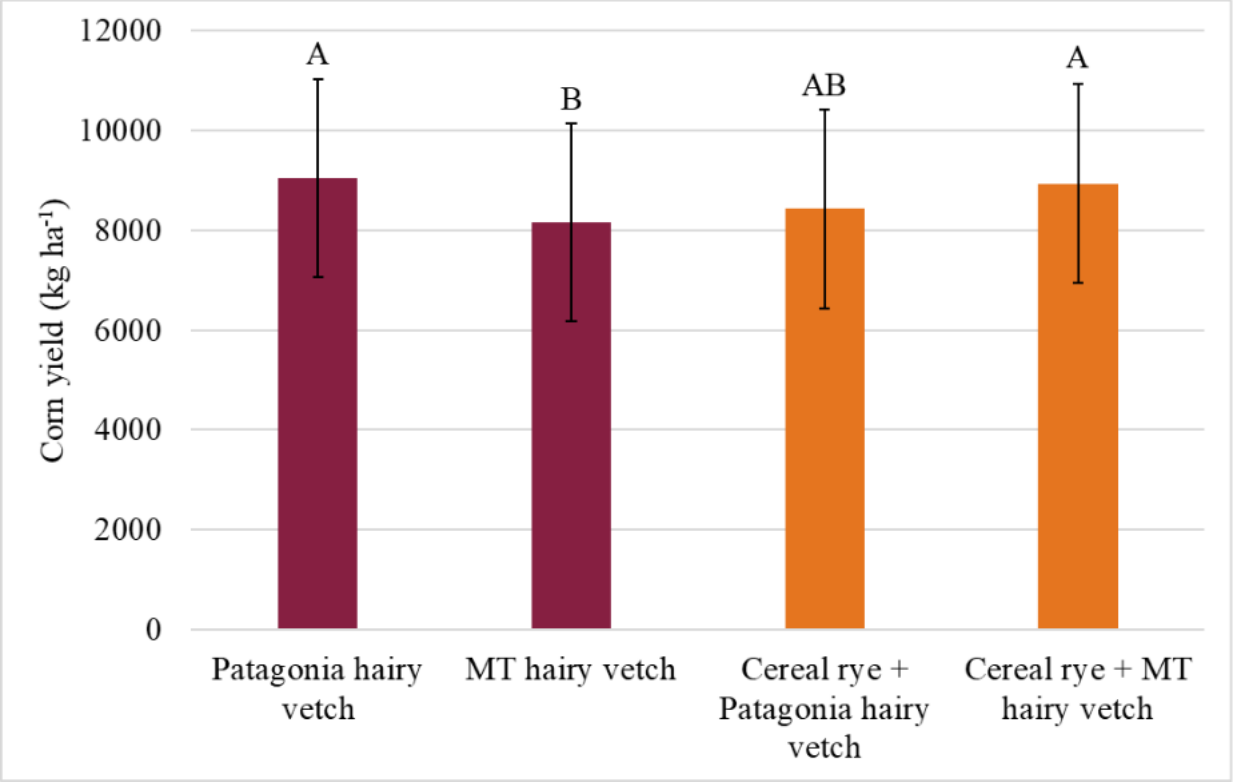


Figure 1.8. Corn yield LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate hairy vetch and cereal rye mixtures while maroon bars indicate hairy vetch monocultures.

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Evaluating Reduced Herbicide Inputs in Corn Following Hairy Vetch, Hairy Vetch + Cereal Rye, or Winter Fallow

Abstract

Progressive Virginia farmers are planting corn (*Zea mays* L.) "green" (terminating the cover crop at corn planting) into a hairy vetch (*Vicia villosa* R.) and cereal rye (*Secale cereale* L.) winter cover crop. Cover crops increase early season weed suppression and, thus, have the potential to reduce herbicide inputs, which has been reported by farmers. The aim of this experiment was to compare the success of hairy vetch, hairy vetch + cereal rye, or winter fallow followed by herbicide programs that included 1-pass terminated 2 weeks before corn planting ("planting brown"), 1-pass green, 2-pass brown, 2-pass green, or 3-pass brown for weed suppression and corn yield. Across 4 site-years in Virginia, cover crop biomass levels ranged from 500 to 4620 kg ha^{-1} at corn planting. One month after corn planting, planting green herbicide programs were within the top performing groups for Palmer amaranth (*Amaranthus palmeri* S. Watson) density as well as the proportion of large crabgrass (*Digitaria sanguinalis* (L.) Scop.), Palmer amaranth, and total weeds >10 cm in height. Planting green programs also provided greater total weed suppression compared to planting brown programs, regardless of cover crop. But compared to either cover crop, no cover provided better large crabgrass density reduction. 2 months after corn planting, both 1-pass programs provided less weed control compared to the 2-pass and 3-pass programs. At this time, no cover had lower weed densities than cover crops. Corn yield was greatest from the 1-pass green and 2-pass herbicide programs and was not influenced by cover crop treatment. Overall, 2-pass herbicide programs in hairy vetch optimized weed suppression, corn yield, and net returns.

Keywords: Planting brown, planting green, weed suppression, biomass, cover crops, corn, cost savings.

Introduction

Cover crop surface residues can suppress weeds in many cropping systems. Typically, the more biomass the cover crop produces the more weed suppression results (Osipitan et al., 2019). The amount of biomass needed for weed control differs depending on the weeds being targeted, the cover crop being used, and the climate of the region (Kumar et al., 2024; Nichols et al., 2020; Weisberger et al., 2023). Mirsky et al. (2013) states 8000 kg ha^{-1} or higher of cereal rye biomass results in sufficient weed suppression. A meta-analysis conducted by Nichols et al. (2020) found that at least 5000 kg ha^{-1} was needed to reduce weed biomass by 75% in the United States' Mid-west. However, Weisberger et al. (2023) states to obtain at least a 50% reduction in weed density in the Southeastern United States, 6600 kg ha^{-1} of cover crop biomass is necessary. For weedy *Amaranthus* species specifically, at least 4079 kg ha^{-1} of biomass was needed to reduce weed densities by 50% and 5352 kg ha^{-1} to reduce weed biomass (Kumar et al., 2024). Regardless of the weed species, there is typically a strong correlation between cover crop biomass and weed suppression (Hodgdon et al., 2016; Kumar et al., 2024; Nichols et al., 2020).

Farmers have also observed weed control benefits of cover crops. According to the National Cover Crop Survey Report from 2022-2023, one of the main goals of using cover crops for farmers is improved weed management (National Cover Crop Survey Report 2022-2023, 2023). This report also states that better weed control has been observed by farmers from cover crops. Because of these reductions in weed pressure, there has been speculation that the use of cover crops can potentially reduce herbicide inputs for farmers (Teasdale, 1996). Bunchek et al.

(2020) determined that substituting cover crops for a PRE herbicide application did not decrease total weed control and ultimately lowered the number of large weeds (>10 cm tall) at POST herbicide applications. This study, as well as farmer reports, emphasizes that cover crops may be able to reduce herbicide inputs needed for effective weed control.

Cover crops can be managed in multiple ways which impact on total weed suppression and ultimately the potential for herbicidal input reductions. There are two main timings of cover crop termination, so-called "planting green" and "planting brown." Planting green is defined as "the practice of planting a row crop into an actively growing cover crop and terminating it at or after row crop planting" (Stephens et al., 2023). This method is associated with benefits such extended soil conservation, more soil moisture in some cases, potential fertilizer cost savings, and reduced slug pressure (Le Gall et al., 2022; Teasdale et al., 2012; Reddy, 2016). Importantly, increased biomass from planting green can result in more weed suppression (Le Gall et al., 2022). Moreover, planting brown is when a cover crop is terminated prior to the cash crop planting which results in the residue becoming brown at planting (Carrijo, 2025). Planting brown can benefit farmers by increasing soil moisture conservation, reducing the risk of reduced cash crop emergence, and resulting in faster nutrient release from cereal species (Balkcom et al., 2015; Otte et al., 2019). The traditional method of planting brown can suppress weeds, but may reduce overall cover crop biomass accumulation and even queue weed emergence and growth due to increased nutrient availability and light penetration which can reduce weed seed dormancy (Lawson et al., 2015, Sias et al., 2021).

No matter the termination timing, the cover crop a farmer chooses to implement plays a crucial role in the benefits it will produce. For this study, we chose to evaluate hairy vetch monocultures and a hairy vetch + cereal rye mixture because of their agronomic benefits and

popularity amongst Virginia corn farmers. Two major benefits of hairy vetch are that it can create thick mats of biomass that lead to weed suppression and produce nitrogen that can later be used by the corn cash crop (Thapa et al., 2018; Reddy and Kroger, 2004). On the other hand, hairy vetch has slow fall establishment and, thus, can struggle to survive harsh winters (Lawson et al., 2015; Wiering et al., 2018). To attempt to reduce this winterkill, farmers pair hairy vetch and cereal rye together as their winter cover crop. Cereal rye has been shown to hairy vetch winter survival (Brainard et al., 2012; Hayden et al., 2015; Thapa et al., 2018). Furthermore, cereal rye alone introduces benefits such as erosion control, greater weed suppression compared to hairy vetch alone, and reducing nutrient leaching (Camargo and Bagavathiannan, 2023; Hayden et al., 2012).

Both the planting green and planting brown methods have their advantages and disadvantages that farmers weigh when determining which to utilize. However, there are currently gaps in the literature regarding comparing planting green and planting brown for their ability to reduce herbicide needs or inputs. To fill part of this gap, the objective of this research is to evaluate the probability of success for 1-, 2-, or 3- pass corn herbicide programs in hairy vetch compared to a cereal rye + hairy vetch mixture and no cover.

Materials and Methods

Study Sites.

To evaluate the probability of success for 1-, 2-, or 3- pass corn herbicide programs in hairy vetch compared to cereal rye + hairy vetch and no cover, the experiment was conducted for two seasons at two locations resulting in a total of four site-years. Studies were initiated in the fall of 2023 and 2024 at Kentland Farm near Blacksburg, VA, USA (37°11'37"N 80°34'21"W)

and Blackstone, VA, USA at the Southern Piedmont Agricultural Research and Extension Center (37°05'00"N 77°58'15"W). The fields at Kentland Farm fell within the New River's floodplain which has a Ross soil and has a taxonomic class of fine-loamy, mixed, superactive, mesic Cumulic Hapludolls. At the Blackstone location, the soil's taxonomic class is fine, kaolinitic, thermic, Typic Kanhapludults and is an Applying coarse sandy loam. In 2023, the Kentland Farm trial was previously in multiple crops while the following year the previous crop was corn. Both years the fields were prepared for cover crop planting by being tilled via a disk and subsequently cultipacked. In 2023 and 2024, the fields at the Blackstone location were previously in soybeans and fallow, respectively. Prior to planting in 2023, the field was cut to roughly 10 cm with a tractor mounted rotary mower and then planted no-till. The following year, the field was sprayed with glyphosate (Roundup Powermax 3; Bayer Crop Science, St. Louis, MO, USA) at a rate of 1262 g ae ha^{-1} and then disked. There were endemic weed populations at each trial location.

Treatments and Experimental Design.

The objective was evaluated using a factorial treatment structure. The first factor was cover crop and was (A) MT hairy vetch alone, (B) MT hairy vetch + cereal rye (Late Abruzzi) mixture, or (C) no cover crop. Herbicide program was the second factor (Table 2.1). Herbicide programs were chosen based on typical corn herbicide programs in Virgina when farmers are looking to use 1-, 2-, or 3-passes. Prior to corn planting, the cover crops were roller crimped before being sprayed and/or planted with corn. The initial herbicide application of each of the five treatments was terminating the cover crop. Postemergent herbicide applications were made when corn was 30 cm tall. Herbicide applications were made using a CO_2 backpack sprayer with a 3 m boom equipped with six TeeJet (Teejet Technologies, Glendale Heights, IL, USA)

XR110015 nozzles. This equipment was calibrated to deliver the herbicide mixture at 140 L ha^{-1} at 207 kPA.

Plots were at least 7.6 m by 3.0 m each year and were arranged in a randomized strip block design with four replications at each location.

Crop Production Practices.

In 2023, cover crops were planted on 4 October and 13 October in Blackstone and Blacksburg, respectively. The following year, planting began on 11 October 2023 in Blackstone and 18 October 2024 in Blacksburg. Cover crops were drilled to a depth of roughly 2.5 cm deep both years. In 2023, the MT hairy vetch at both locations was unintentionally planted 91 kg ha^{-1}. In 2024, the hairy vetch was planted at 22 kg ha^{-1} at both locations. The cereal rye at either location was planted 84 kg ha^{-1} for both years.

For each of the treatments, corn, variety DKC110-10RIB (Dekalb Acceleron Seed Treatment) (Bayer Crop Science, St. Louis, MO, USA) was planted at 72376 seeds per hectare with 76 cm row spacings. In 2024, corn was planted in Blackstone and Blacksburg on April 15th and April 24th, respectively. The following year, corn was planted in Blackstone on April 16th and in Blacksburg on April 23rd. Within a week of planting at all site-years, the corn was fertilized with roughly 56 to 67 kg N ha^{-1}. Around one month after planting, the corn was fertilized again with 129 kg N ha^{-1} in Blackstone both years and Blacksburg in 2024 in the form of either 46-0-0 or 34-0-0. In 2025, the corn in Blacksburg received 183 kg N ha^{-1} in the form of 46-0-0. On June 4th, elemental sulfur (90%) was also applied in Blackstone at 28 kg ha^{-1} to combat a sulfur deficiency.

Data Collection.

Cover crop biomass samples were collected at the time of cover crop termination, which varied by herbicide program. Two weeks prior to corn planting, four cover crop biomass samples from herbicide programs 1, 3, and 5 were taken from both the hairy vetch + cereal rye plots and the hairy vetch monoculture plots using a randomly placed 0.25 m^2 quadrat. Biomass samples were not taken from the winter fallow plots. At corn planting, four biomass samples were taken from herbicide programs 2 and 4 using the same technique. Samples were dried to a constant weight and weight. Homogenized subsamples were later subjected to nutrient content analysis for carbon and nitrogen content via near-infrared spectroscopy.

One month after corn planting, data were collected on weed density and weeds over 10 cm for the top four most abundant weed species at each site-year and were taken from the middle interrow of each plot. For weeds that had dense stands, 0.5 m^2 quadrats were utilized to collect a representative sample of the entire plot. For weeds stands that were less dense, the all weeds within the middle interrow of each plot were counted. Palmer amaranth (*Amaranthus palmeri* S. Watson) was among the top four weed species in all site-years. In Blackstone in 2023, other weeds counted consisted of large crabgrass (*Digitaria sanguinalis* (L.) Scop.), common ragweed (*Ambrosia artemisiifolia* L.), and giant foxtail (*Setaria faberi* H.). In Blacksburg the same year, the weeds counted were large crabgrass, common ragweed, and morningglory species (*Ipomoea spp.*). The following year in Blacksburg, other weed species counted included morningglory species, yellow nutsedge (*Cyperus esculentus* L.), and pokeweed (*Phytolacca americana* L.). That same year weeds sampled at Blackstone consisted of large crabgrass, giant foxtail, and goosegrass (*Eleusine indica* (L.) Gaertn.) were the weed species sampled. One month later in June, 4 weeks after the postemergent herbicide application, weed density data on the same weeds were taken again.

Corn yield data were collected from the center two rows of each plot. At both locations in 2024 and in Blacksburg in 2025, the harvest area of each plot was 1.5 m by 6 m. In 2025, the harvest area in Blackstone was 1.5 m by 7.6 m. In 2024, the plots were harvested on September 10th and October 29th in Blackstone and Blacksburg, respectively. The following year, corn was harvested in Blackstone on September 23rd and in Blacksburg on October 7th.

Net Return.

To compare the costs of all cover crop and herbicide programs, an economic analysis was conducted (Table 2.2). Net return was calculated using yield data and costs as well as corn price from the Cover Crop Economic Decision Support Tool (ECC-ECON) as well as the University of Maryland Extension's 2025 Field Crop Budget (*CC-Econ*, 2025; Dill et al., 2025).

Data Analysis.

The biomass, weed suppression, and yield data were all analyzed using JMP (JMP Pro 18, SAS Institute, Inc., Cary, NC. USA). All data were subjected to analysis of variance (ANOVA). Cover crop was the only fixed effect for cover crop biomass two weeks prior to planting. Cover crop biomass at corn planting, all weed species, and corn yield data had fixed effects of cover crop, herbicide program, and their interaction. Only weeds that occurred at more than two site-years were statistically analyzed. Thus, weeds evaluated included large crabgrass, Palmer amaranth, common ragweed, morningglory species, and giant foxtail. Total weeds were also included. Site-year and replications nested within site-year were considered random effects. After ANOVA, means separation was conducted using a Student's T test ($p \leq 0.05$). Prior to analysis, all data were transformed to meet a normal distribution. If transformations did not improve normality, analysis was conducted on untransformed data.

Results and Discussion

Cover Crop Biomass Accumulation.

Two weeks prior to corn planting, the hairy vetch + cereal rye mixture had significantly ($p = 0.005$) greater amounts of biomass compared to hairy vetch alone (Figure 2.1). At this time, the cover crop mixture and the hairy vetch monoculture had accumulated, on average, about 2090 and 1610 kg ha^{-1} of biomass, respectively. Two weeks later at corn planting, there were no biomass differences ($p = 0.41$) between the cover crop mixture and the hairy vetch monoculture and neither cover crop treatment had accumulated more than 2875 kg ha^{-1} of biomass (Figure 2.1). Thus, the results for both cover crop termination timings indicated that while the hairy vetch + cereal rye mixture will provide more biomass for earlier termination, if termination is delayed until planting, the monoculture will provide similar biomass as the mixture.

When comparing the biomass from two weeks prior to planting and at planting, the later termination allowed for the accumulation of 962 kg ha^{-1} or more cover crop biomass. A study conducted by Nunes et al. (2024) found that waiting to terminate a cereal rye cover crop until soybean planting allowed for a 33% biomass increase compared to an earlier termination. However, previous research has found that while waiting to terminate a cover crop can increase its biomass accumulation, it can also impact herbicide deposition (Smith et al., 2025). 5000 kg ha^{-1} of cover crop biomass in this study reduced herbicide deposition by 50% whereas 2000 kg ha^{-1} only resulted in a 35% reduction relative to bare ground. Ultimately, Virginia farmers can utilize either a hairy vetch monoculture or hairy vetch + cereal rye mixture and obtain similar biomass accumulation at corn planting.

Weed Density.

One month after planting, herbicide program was significant ($p<0.05$) for all weeds except for total weeds and morningglory species (Figures 2.3, 2.4, 2.5) (Tables 2.3, 2.4, 2.5). In general, herbicide programs 2 and 4, both of which were planting green, were among the statistical grouping with the least weed density. Weeds over 10 cm tall followed a similar trend at this sample timing (Figures 2.6 & 2.7)(Tables 2.3, 2.6, 2.7). Cover crop was also a significant factor ($p<0.05$) in weed densities for large crabgrass, common ragweed, morningglory species, giant foxtail, and total weeds. The presence of a cover crop resulted in a ~28% reduction in common ragweed plants and a decrease of around 2 weeds m^{-2} for morningglory species. However, cover crops resulted in greater weed densities for total weeds, giant foxtail, and large crabgrass. For example, large crabgrass densities increased from 4 plants m^{-2} with no cover crop up to 11 plants m^{-2} with a hairy vetch + cereal rye mixture. Similarly, giant foxtail densities increased from 3 plants m^{-2} to 7 or 11 plants m^{-2} with the presence of cover crops. Cover crop programs also resulted in less common ragweed over 10 cm tall as well. Overall, these results show that the additional cover crop biomass and later herbicide applications from planting green caused better overall weed suppression compared to planting brown herbicide application timings. However, no cover with later herbicide applications provided better weed suppression for certain weeds. Thus, at the time of postemergence herbicide application, there is potential for reducing herbicide inputs through the use of herbicide programs and planting green.

Two months after corn planting, herbicide program was generally more important for weed control compared to cover crop species or presence. Large crabgrass showed that the 2-pass or 3-pass herbicide programs provided better weed suppression with no cover crop (Figure 2.8). These results may be due to the large crabgrass having better establishment prior to later herbicide applications because the cover crops intercepted more of the herbicides that were

applied. Season-long Palmer amaranth densities were reduced the most by herbicide programs with >1 pass and cover crop presence (Figure 2.9). Cover crops decreased common ragweed presence by up to 55.9% while herbicide programs where cover crops were planted green into typically provided greater suppression compared to planting brown programs. For total weeds, the no cover crop treatment contained roughly 14 weeds m^{-2} while hairy vetch and hairy vetch + cereal rye resulted in around 18 and 21 weeds m^{-2}, respectively (2.10). Like Palmer amaranth, herbicide programs containing >1 pass resulted in a decrease in total weeds by an average of 48 weeds compared to the 1-pass programs (Figure 2.11).

Less than a 1-pass herbicide programs also enhanced weed suppression for total weeds. Ultimately, these data indicate that while a 1-pass herbicide program results in sufficient weed suppression earlier in the season, for season-long suppression a more robust program is needed. Thus, farmers in the mid-Atlantic region who are looking to optimize their season-long weed suppression should implement at least a 2-pass herbicide program.

Previous literature states that the presence of cover crops compared to fallow should result in more overall weed suppression (Baraibar et al., 2018; Osipitan et al., 2019; Smith et al., 2020). While this was supported by 1 month after corn planting results for the broadleaf species in this study, this trend was not always the case for either grass species. Both grass species were less dense when there was no cover crop. Higher densities of grass weeds in plots containing cover crops may be due to nitrogen release from the leguminous hairy vetch or because the cover crop interfered with the residual herbicide deposition to the soil (Smith et al., 2025; Sias et al., 2021). Moreover, cover crop biomass levels were far less than previous research states they need to be in order to have significant weed suppression. These results may have differed if there were greater levels of cover crop biomass at termination. According to a meta-analysis conducted by

Weisberger et al. (2023), at least 6600 kg ha^{-1} of cover crop biomass was needed to reduce weed density by 50% in the Southeastern United States. Moreover, we also did not see the expected results from the cover crop treatments two months after corn planting. We expected to see cover crop treatments suppressing more weeds compared to the winter fallow, which was not the case. This finding was likely due to similar reasons previously mentioned such as low cover crop biomass, a nitrogen release from the hairy vetch, and potentially herbicide immobilization from the cover crop.

Yield

Cover crop was not a significant factor in yield, however, herbicide program was (Figure 2.12). Prior research has shown that cover crops species do not always impact corn yields (Blanco-Canqui et al., 2015; Marcillo et al., 2017). With that being said, many studies show that there is a positive correlation between leguminous cover crops and higher corn yields. For example, a meta-analysis conducted by Marcillo et al. (2017) found that on average, a legume cover crop increase corn yields by 30% when the cover crop was terminated later in the season. The results from our study may not demonstrate that relationship because of the low biomass accumulation likely leading to less nitrogen available for the following corn cash crop.

Herbicide program was a significant factor for corn yield. Similar to weed density results, herbicide programs 2 and 4 were among the top statistical groupings for corn yield. This indicates that planting green appeared to result in greater overall corn yields compared to those herbicide programs that resulted in the corn to be planted brown. This aligns with some previous literature that states the additional biomass gained when a hairy vetch cover crop is terminated later results in better overall corn yields due to soil water conservation and more available

nutrients (Clark et al., 1995; Clark et al., 1994; Marcillo et al., 2017; Teasdale and Shirley, 1998). However, it also contradicts other research that states waiting too long to terminate a cereal rye and/or hairy vetch cover crop can lead to reduced soil moisture and ultimately lower yields (Godar et al., 2024; Kumar, 2023). Ultimately, based on these findings, farmers looking to increase their overall corn yields should consider terminating their hairy vetch + cereal rye cover crop until corn planting and planting green.

Net return.

The same herbicide programs that maximized yield (1-pass planted green and 2-pass) also resulted in the highest net return within the no cover and hairy vetch cover crop treatments (Table 2.2). The cereal rye + hairy vetch mixture treatments were generally the least profitable. While some herbicide programs within no cover provided the greatest net return, it is difficult to put a price on the soil health benefits provided by a hairy vetch cover crop. Additionally, hairy vetch may allow farmers to reduce fertilizer inputs, further increasing net return. This cost analysis also does not include Virginia's cover crop subsidies, which may help to offset cover crop seed and planting costs. Ultimately, farmers in Virginia could reduce their herbicide inputs from 3 passes to 1-2 without reducing their total profits.

Practical Implications.

Planting green allows for greater cover crop biomass production which, in addition to our findings, is known to increase benefits from the cover crop such as increased nitrogen production and potential fertilizer reductions (Reddy, 2016). The current study shows that there is potential for herbicide inputs to be reduced, as demonstrated by reduced weed densities and less weeds > 10 cm (4 inches) in height one month after corn planting. However, after two months, >1 pass herbicide programs had fewer overall weeds. Thus, in light of herbicide resistance, farmers

should consider 2-pass herbicide programs to optimize their weed control, cash crop yield, and monetary inputs.

Tables

Table 2.1 Herbicide programs, timings, and rates for 1-, 2- and 3-pass programs evaluated in field experiments in Virginia in 2023 to 2025.

Time	Herbicide Programs				
	1: Planted Brown 1-pass	2: Planted Green 1-pass	3: Planted Brown 2-pass	4: Planted Green 2-pass	5: Planted Brown 3-pass
2 Weeks Prior to Planting	Acuron (*S*-metolachlor (1500 g ai ha^{-1}) + atrazine (701 g ai ha^{-1}) + mesotrione (168 g ai ha^{-1}) + bicyclopyrone (42 g ai ha^{-1}))[a]		Bicep II Magnum (atrazine (1826 g ai ha^{-1}) + *S*-metolachlor (1414 g ai ha^{-1}))[a]		Glyphosate (1262 g ae ha^{-1})
	Glyphosate (1262 g ae ha^{-1})[a]		Glyphosate (1262 ae g ha^{-1})		2,4-D LV4 (533 g ae ha^{-1})[a]
At Planting		Acuron (*S*-metolachlor (1500 g ai ha^{-1}) + atrazine (701 g ai ha^{-1}) + mesotrione (168 g ai ha^{-1}) + bicyclopyrone (42 g ai ha^{-1}))		Bicep II Magnum (atrazine (1826 g ai ha^{-1}) + *S*-metolachlor (1414 g ai ha^{-1}))	Bicep II Magnum (atrazine (1826 g ai ha^{-1}) + *S*-metolachlor (1414 g ai ha^{-1}))
		Glyphosate (1262 g ae ha^{-1})		Glyphosate (1262 ae g ha^{-1})	Glyphosate (1262 ae g ha^{-1})
Postemergence when corn is 30 cm tall			Halex GT (*S*-metolachlor (1055 g ai ha^{-1}) + glyphosate (1055 g ae ha^{-1}) + mesotrione (106 g ai ha^{-1}))[a]	Halex GT (*S*-metolachlor (1055 g ai ha^{-1}) + glyphosate (1055 g ae ha^{-1}) + mesotrione (106 g ai ha^{-1}))	Halex GT (-metolachlor (1055 g ai ha^{-1}) + glyphosate (1055 g ae ha^{-1}) + mesotrione (106 g ai ha^{-1}))

[a]Sources of manufacturing include Syngenta (Acuron, Bicep II Magnum, Halex GT), Bayer CropScience (Roundup Powermax 3), and Winfield United (2,4-D LV).

Table 2.2 Cover crop and herbicide program treatments cost, yield and net return for field experiments in Virginia in 2023 to 2025.

Cover crop	Herbicide program[d]	Treatment cost ($ ha^{-1})[ab]	Yield (bu ha^{-1})	Net return ($ ha^{-1})[c]
No cover	1	1645.67	233	1026.20
	2	1645.67	283	1600.49
	3	1677.73	280	1540.31
	4	1677.73	280	1536.14
	5	1718.90	241	1053.67
Hairy vetch	1	1816.25	223	745.97
	2	1816.25	298	1611.44
	3	1848.31	273	1290.22
	4	1848.31	288	1455.80
	5	1889.48	222	659.40
Hairy vetch + cereal rye	1	1923.74	222	622.48
	2	1923.74	227	688.26
	3	1955.81	257	996.71
	4	1955.81	279	1250.52
	5	1996.97	282	1242.61

[a]All production costs and corn price were determined using the University of Maryland Extension's 2025 Field Crop Budgets (Dill et al., 2025).
[b]Cover crop prices were determined using the Cover Crop Economic Decision Support Tool (*CC-Econ*, 2025). Hairy vetch and cereal rye seeding rates were 20 and 75 lb ac^{-1}, respectively.
[c]The corn sale price used for this analysis was $11.49 bu^{-1}.
[d]Herbicide programs are presented in Table 2.1.

Table 2.3. Common ragweed density 1 and 2 months after corn planting from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$) within category. Significant effects are presented according to ANOVA.

1 Month After Corn Planting			>10 cm 1 Month After Corn Planting			2 Months After Corn Planting		
Cover Crop*Herbicide Program[a]	Least Square Mean (Weed m^{-2})		Cover Crop	Least Square Mean (% of Weeds >10 cm)		Cover Crop	Least Square Mean (Weed m^{-2})	
Hairy vetch, 2	1.44	FG	Hairy vetch + cereal rye	0.78	AB	Hairy vetch	1.74	B
Hairy vetch, 3	5.82	B-E	No cover	2.65	A	Hairy vetch + cereal rye	2.12	B
Hairy vetch, 4	1.10	G				No cover	3.95	A
Hairy vetch, 5	9.63	AB						
Hairy vetch + cereal rye, 1	3.16	DEF						
Hairy vetch + cereal rye, 2	2.22	FG						
Hairy vetch + cereal rye, 3	6.52	A-D						
Hairy vetch + cereal rye, 4	2.93	EF				Herbicide Program		
Hairy vetch + cereal rye, 5	7.94	AB				1	1.57	C
No cover, 1	3.47	C-F				2	2.44	ABC
No cover, 2	2.86	EFG				3	3.06	AB
No cover, 3	6.80	ABC				4	1.91	BC
No cover, 4	11.94	A				5	3.89	A
No cover, 5	6.79	A-D						

[a] Herbicide programs are presented in Table 2.1.

Table 2.4. Morningglory species density 1 and 2 months after corn planting from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$) within category. Significant effects are presented. according to ANOVA.

1 Month After Corn Planting			>10 cm 1 Month After Corn Planting			2 Months After Corn Planting		
Cover Crop	Least Square Mean (Weed m^{-2})		Herbicide Program[a]	Least Square Mean (% of Weeds >10 cm)		Cover Crop	Least Square Mean (Weed m^{-2})	
Hairy vetch	3.55	B	1	0.10	BC	Hairy vetch	3.74	B
Hairy vetch + cereal rye	4.73	A	2	0.00	C	Hairy vetch + cereal rye	5.88	AB
No cover	5.98	A	3	0.94	AB	No cover	5.34	AB
			4	0.00	C			
			5	1.19	A			

[a] Herbicide programs are presented in Table 2.1.

Table 2.5. Giant foxtail density 1 and 2 months after corn planting from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$) within category. Significant effects are presented according to ANOVA.

1 Month After Corn Planting			>10 cm 1 Month After Corn Planting			2 Months After Corn Planting		
Cover Crop	Least Square Mean (Weed m^{-2})		Herbicide Program	Least Square Mean (% of Weeds >10 cm)		Herbicide Program	Least Square Mean (Weed m^{-2})	
Hairy vetch	10.56	A	2	5.68	C	2	1.24	A
Hairy vetch + cereal rye	7.39	A	3	29.23	B	3	0.09	B
No cover	3.33	B	4	16.81	BC	4	0.20	B
Herbicide Program			5	47.83	A	5	0.15	B
1	10.85	A						
2	4.65	BC						
3	7.83	AB						
4	2.99	C						
5	8.99	AB						

Figures

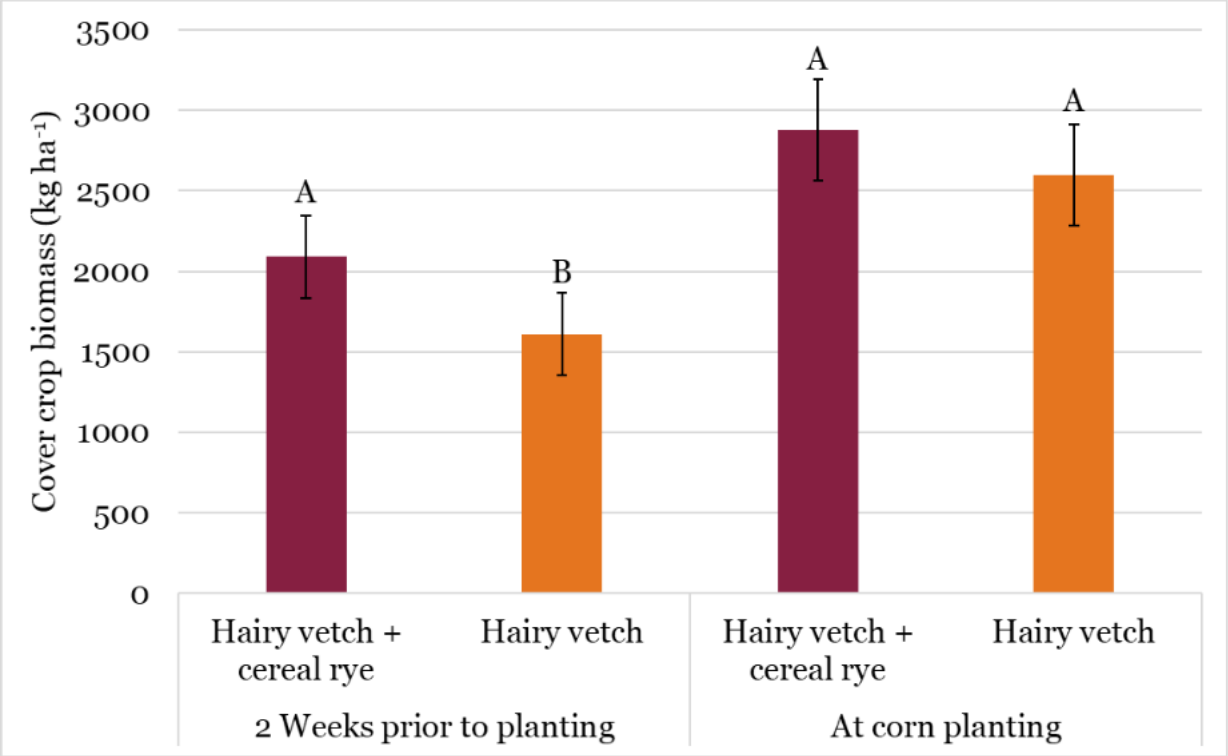

Figure 2.1. Cover crop biomass 2 weeks prior to corn planting ("planting brown") and at corn planting ("planting green") LS means (with SE bars) by sampling timing from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$) within each sample timing.

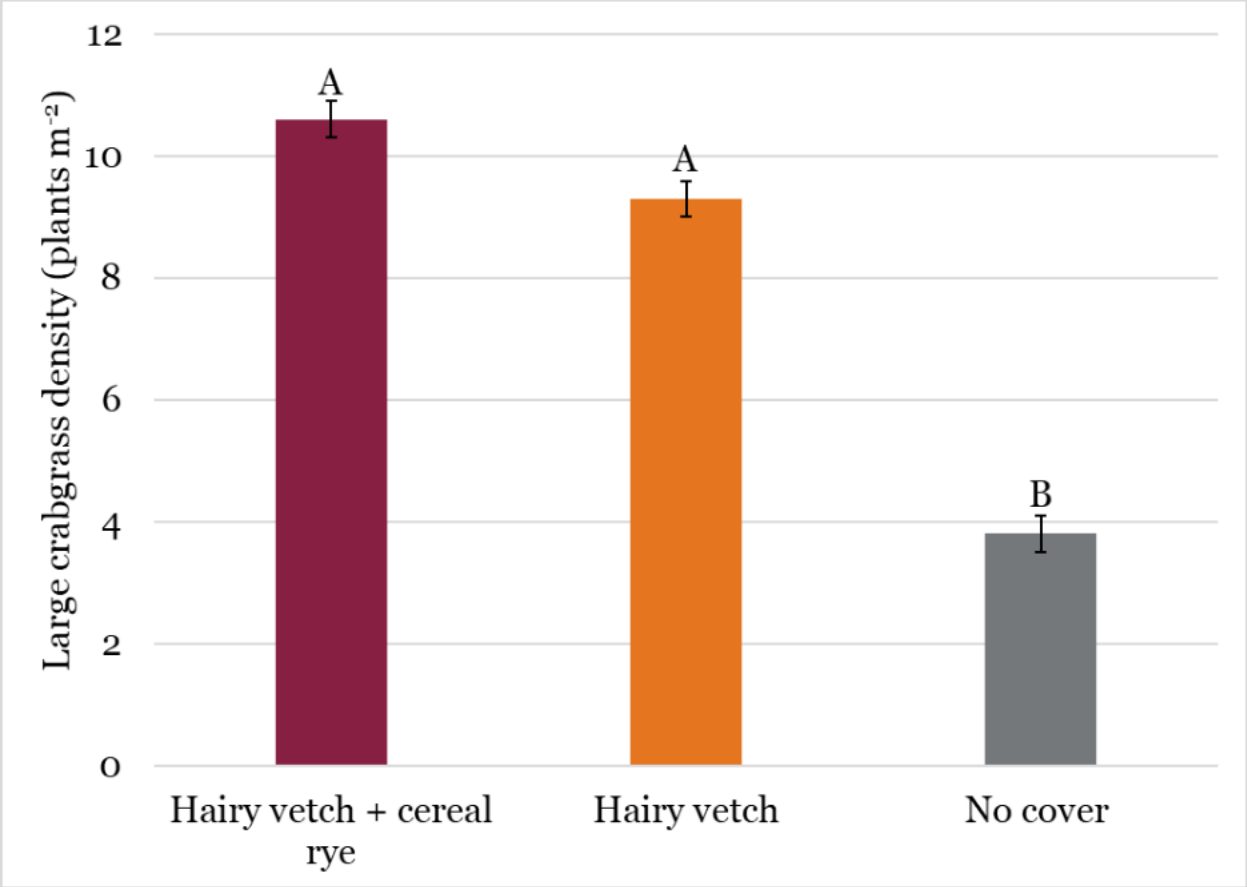

Figure 2.2. Large crabgrass LS means (with SE bars) 1 month after corn planting by cover crop from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$).

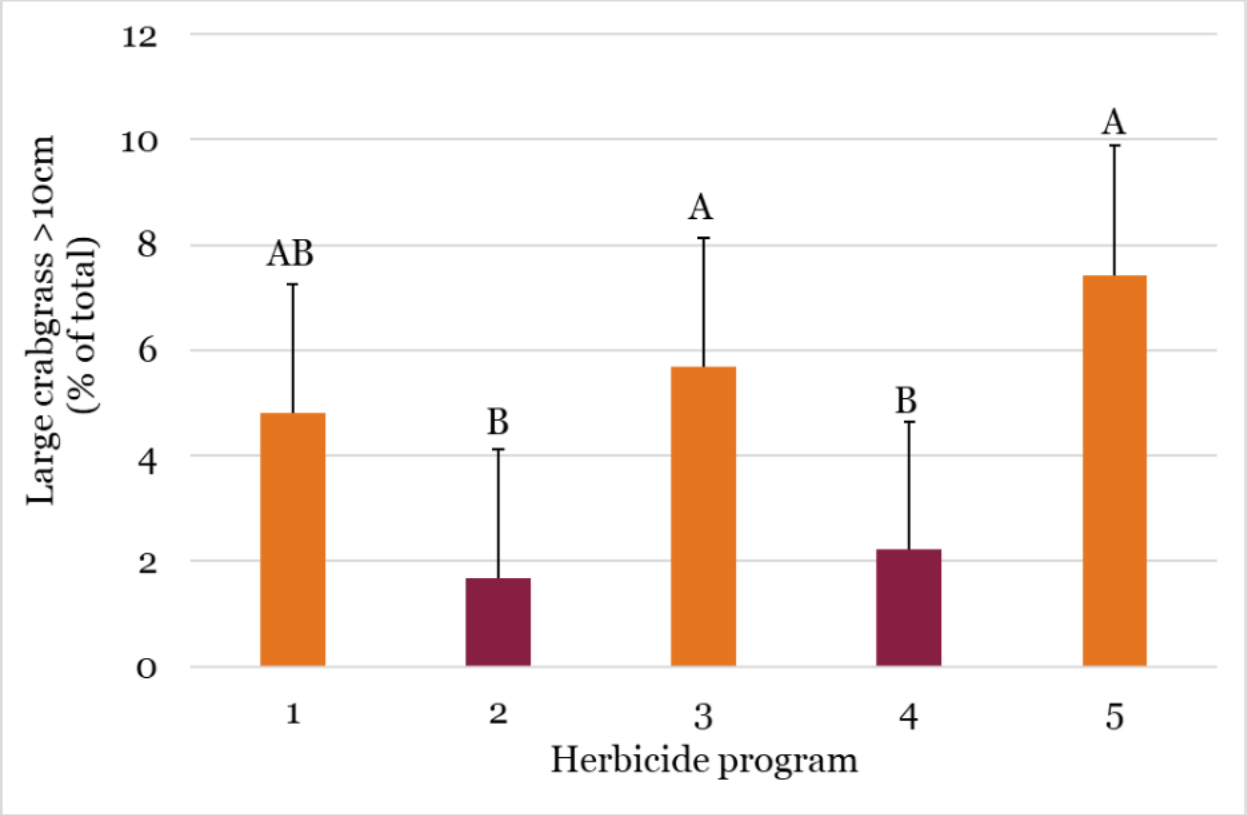

Figure 2.3. Proportion of large crabgrass >10 cm 1 month after corn planting by herbicide program. Data are LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

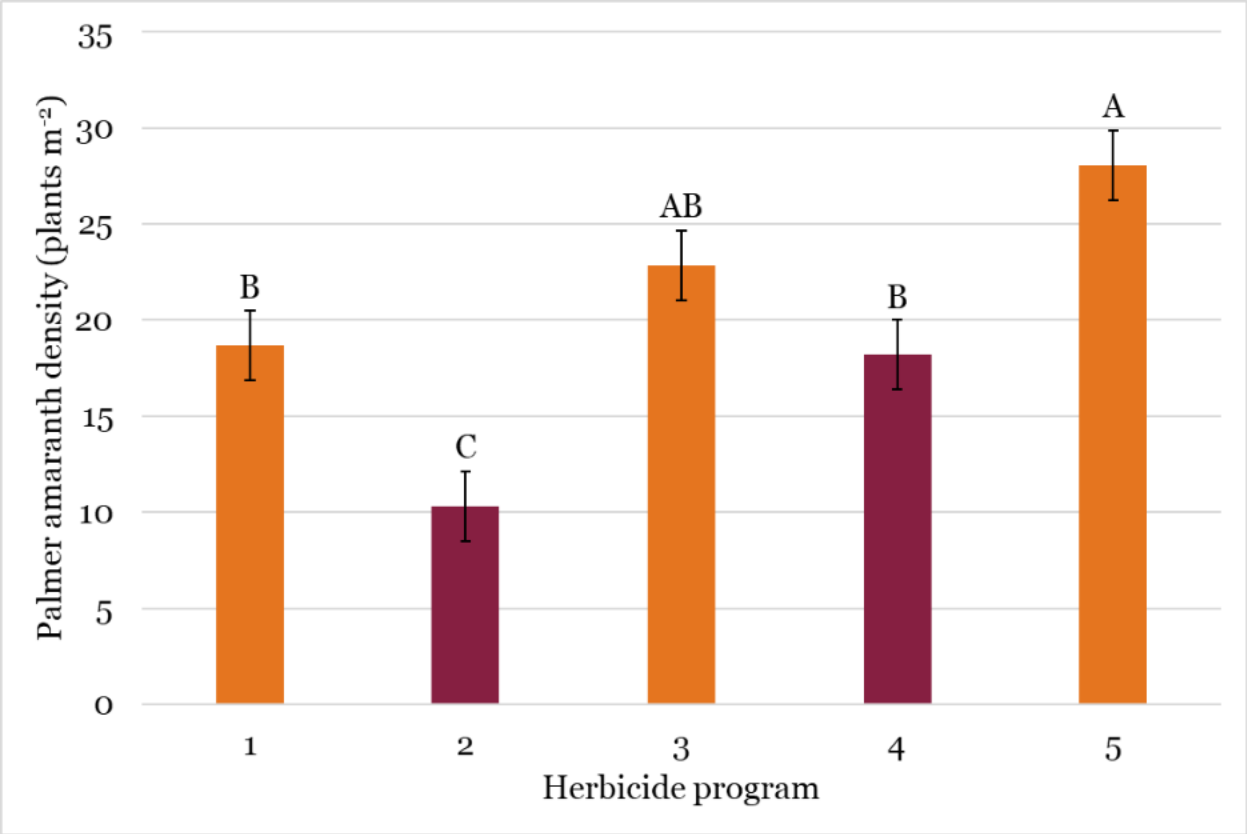

Figure 2.4. Palmer amaranth LS means (with SE bars) 1 month after corn planting by herbicide program. Data are from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

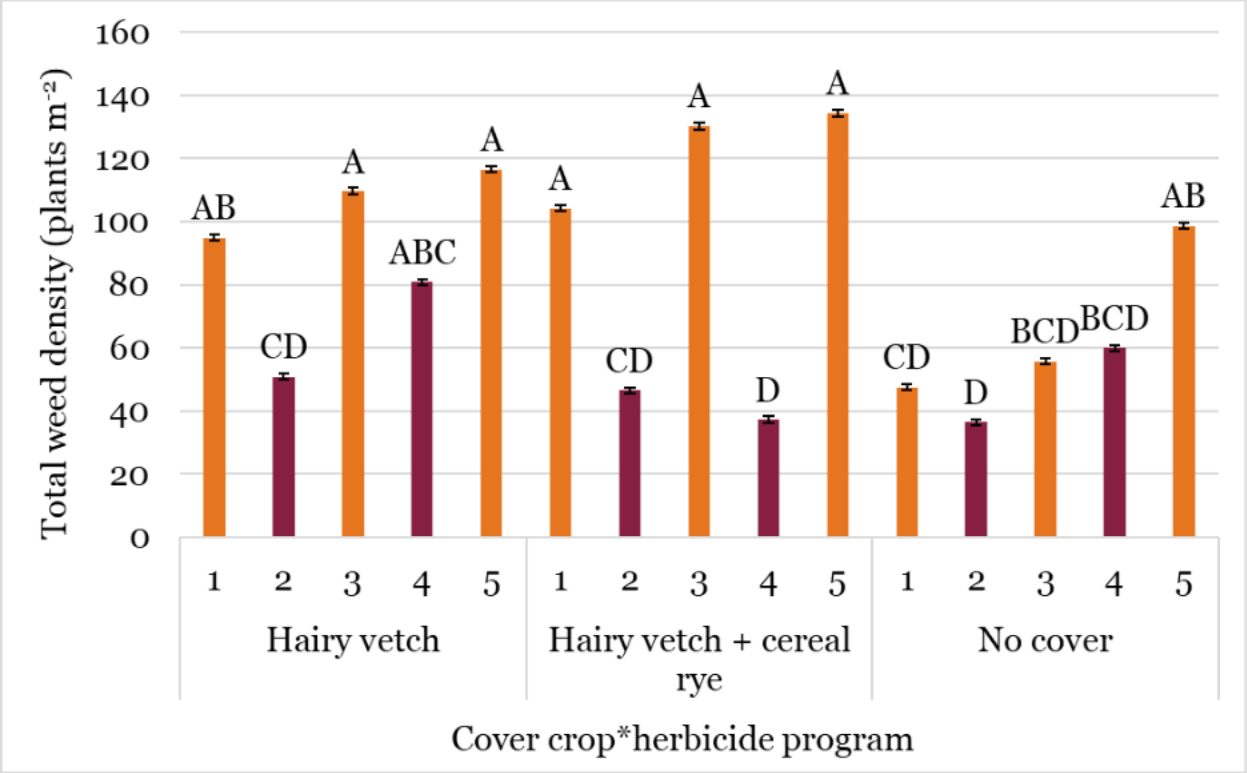

Figure 2.5. Total weed LS means (with SE bars) 1 month after corn planting by the interaction between cover crop and herbicide program. Data are from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

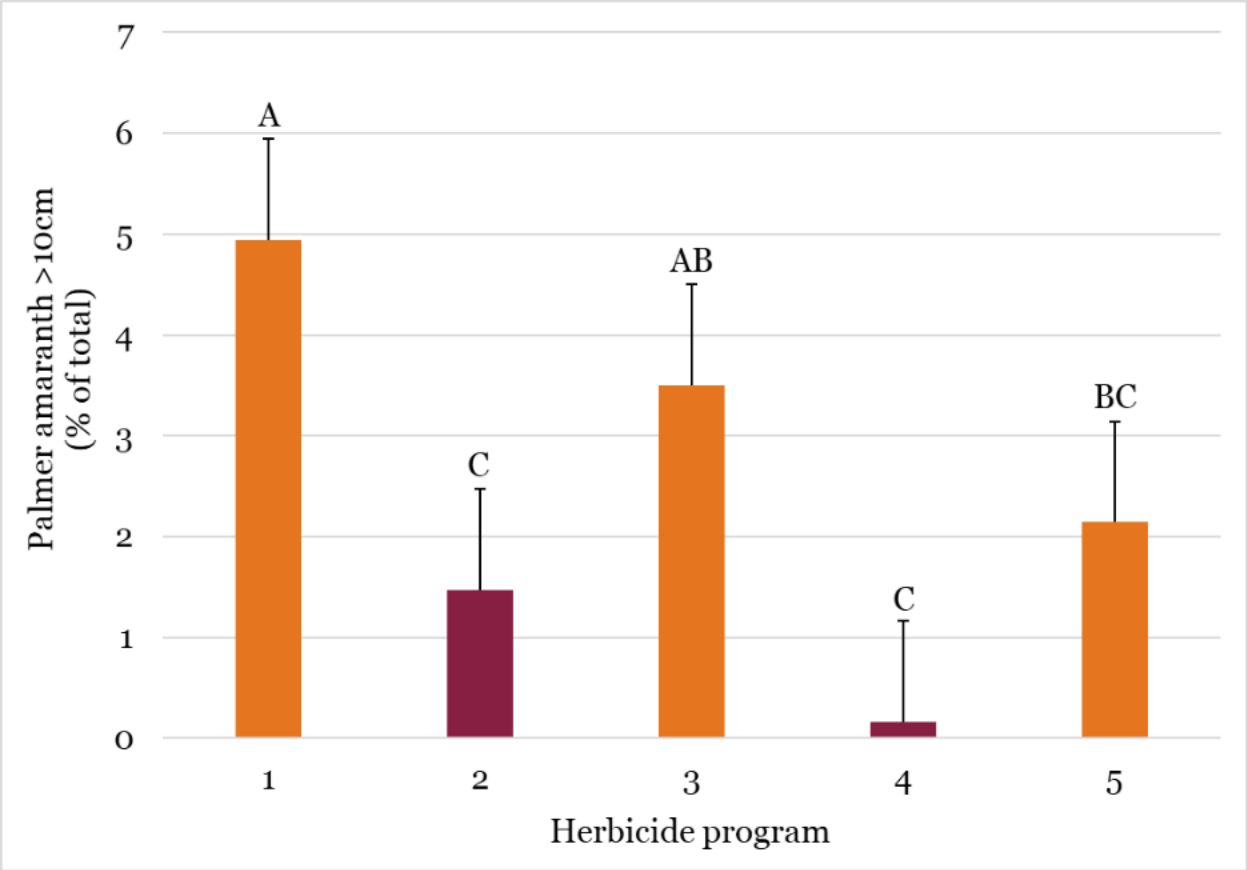

Figure 2.6. Proportion of Palmer amaranth >10 cm 1 month after corn planting by herbicide program. Data are LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

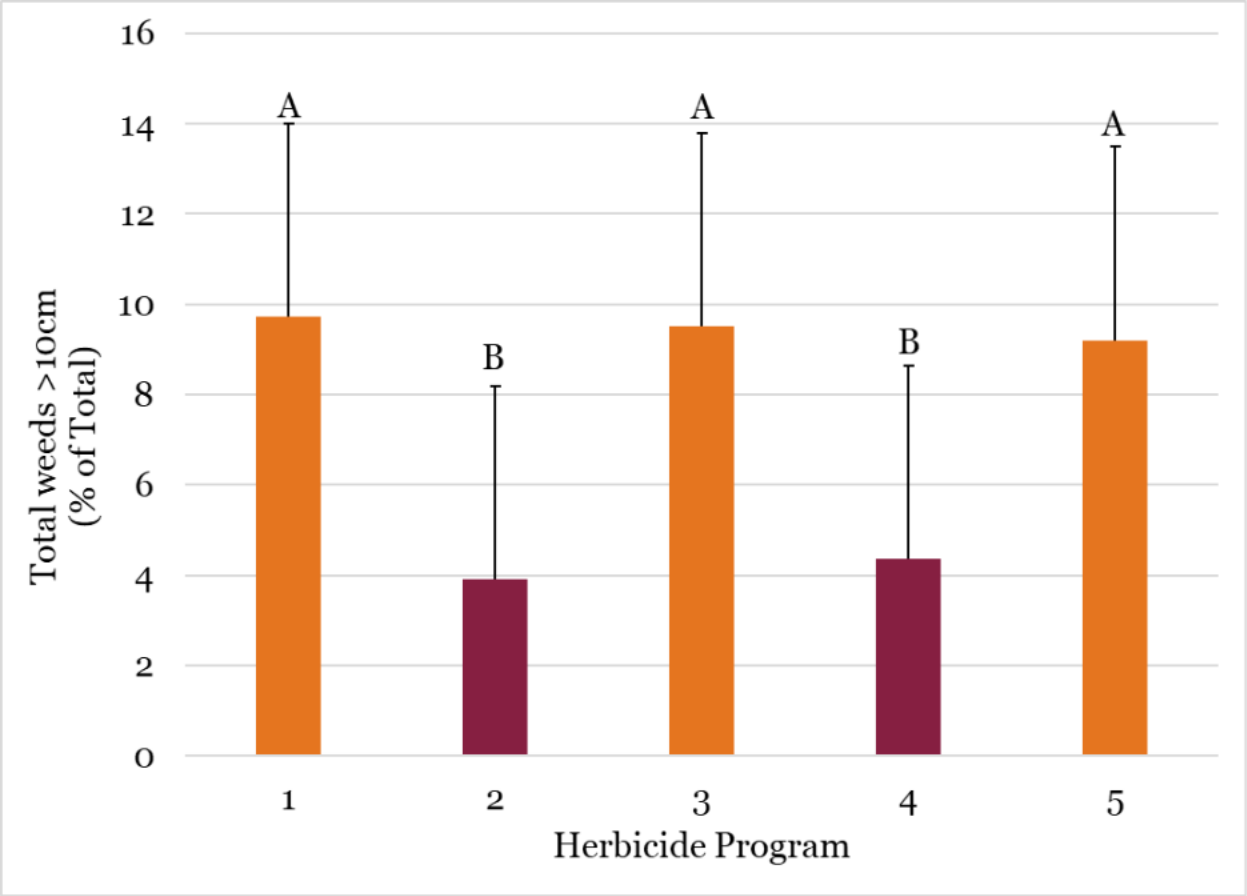

Figure 2.7. Proportion of total weeds >10 cm 1 month after corn planting by herbicide program Data are LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

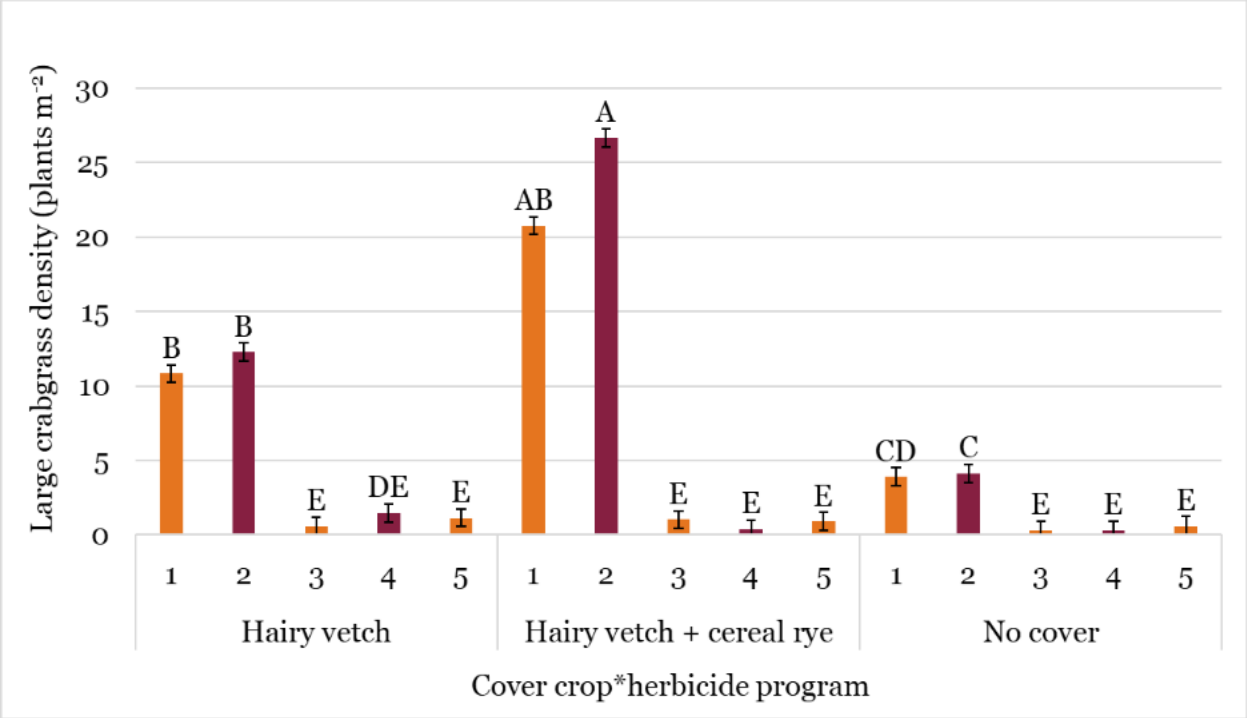

Figure 2.8. Large crabgrass density 2 months after corn planting by the interaction between cover crop and herbicide program. Data are LS means (with SE bars) from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

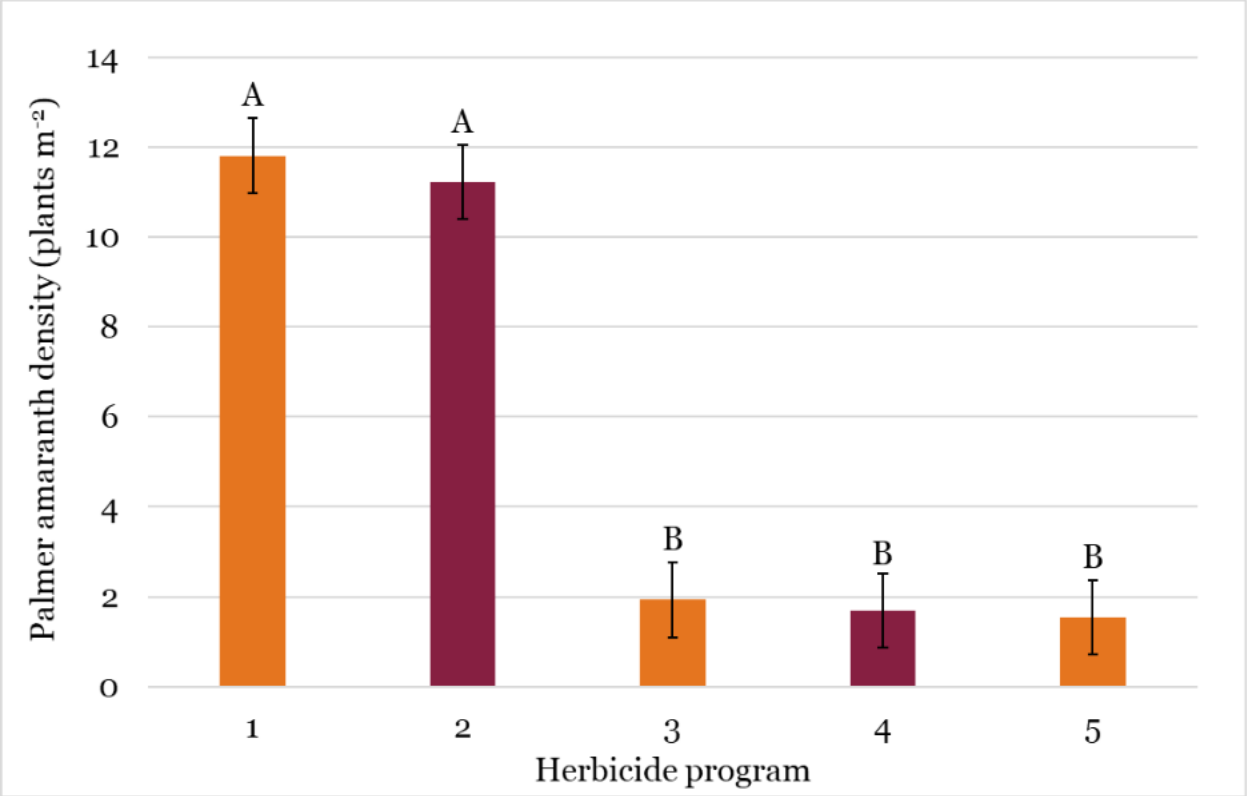

Figure 2.9. Palmer amaranth LS means (with SE bars) 2 months after corn planting by herbicide program. Data are from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

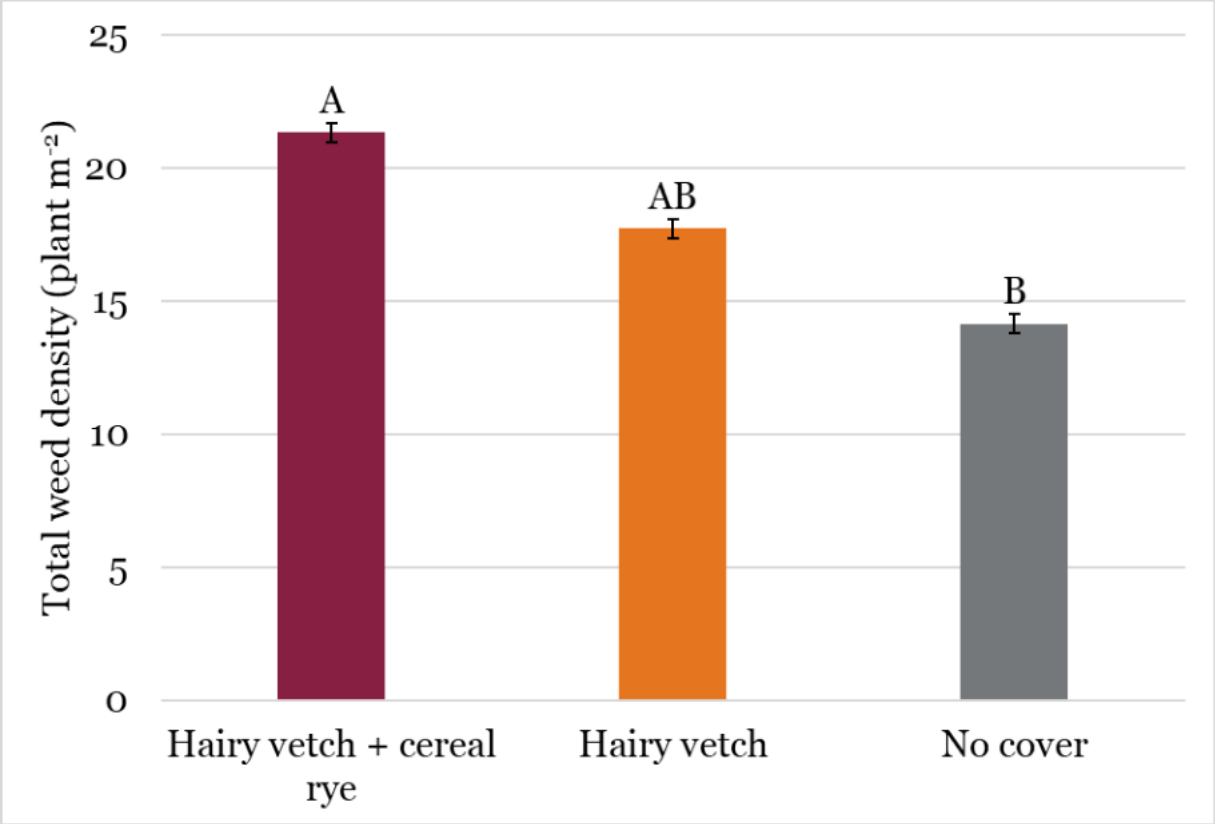

Figure 2.10. Total weed LS means (with SE bars) 2 months after planting from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$).

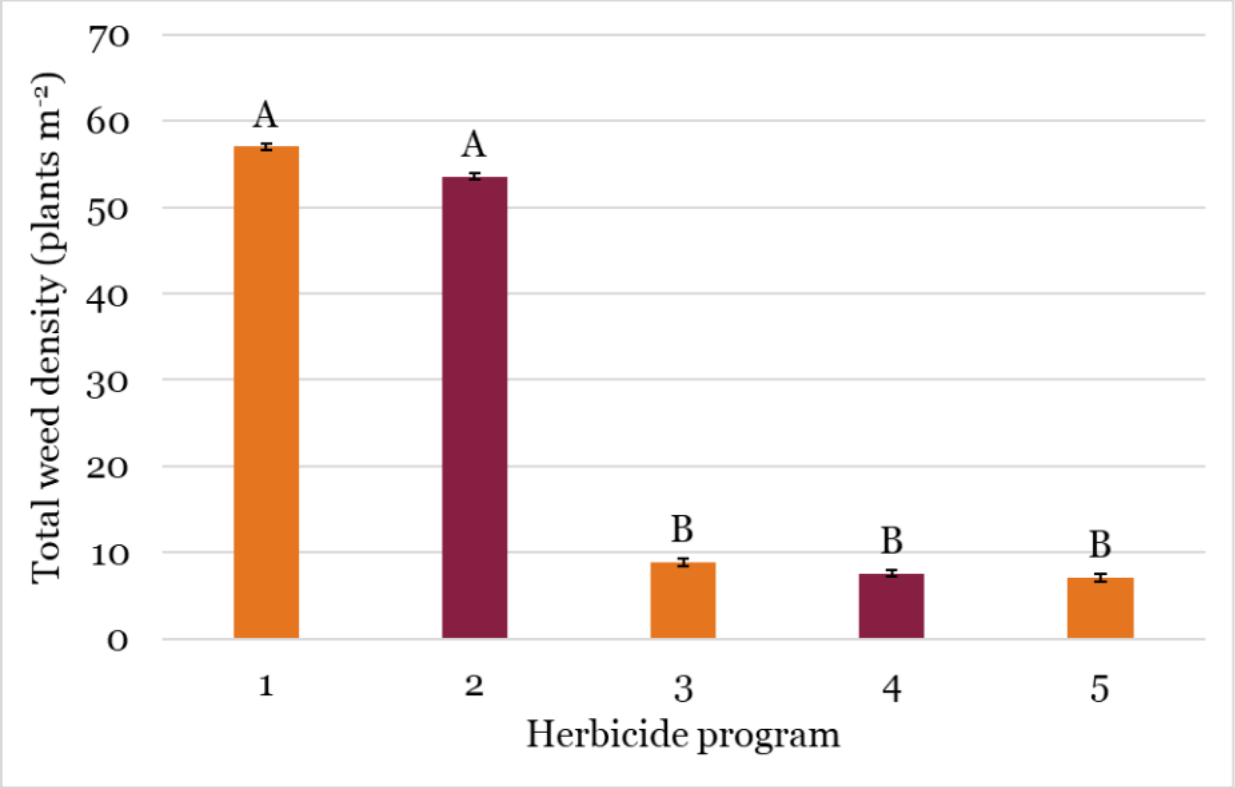

Figure 2.11. Total weed density (with SE bars) 2 months after corn planting by herbicide program. Data are from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

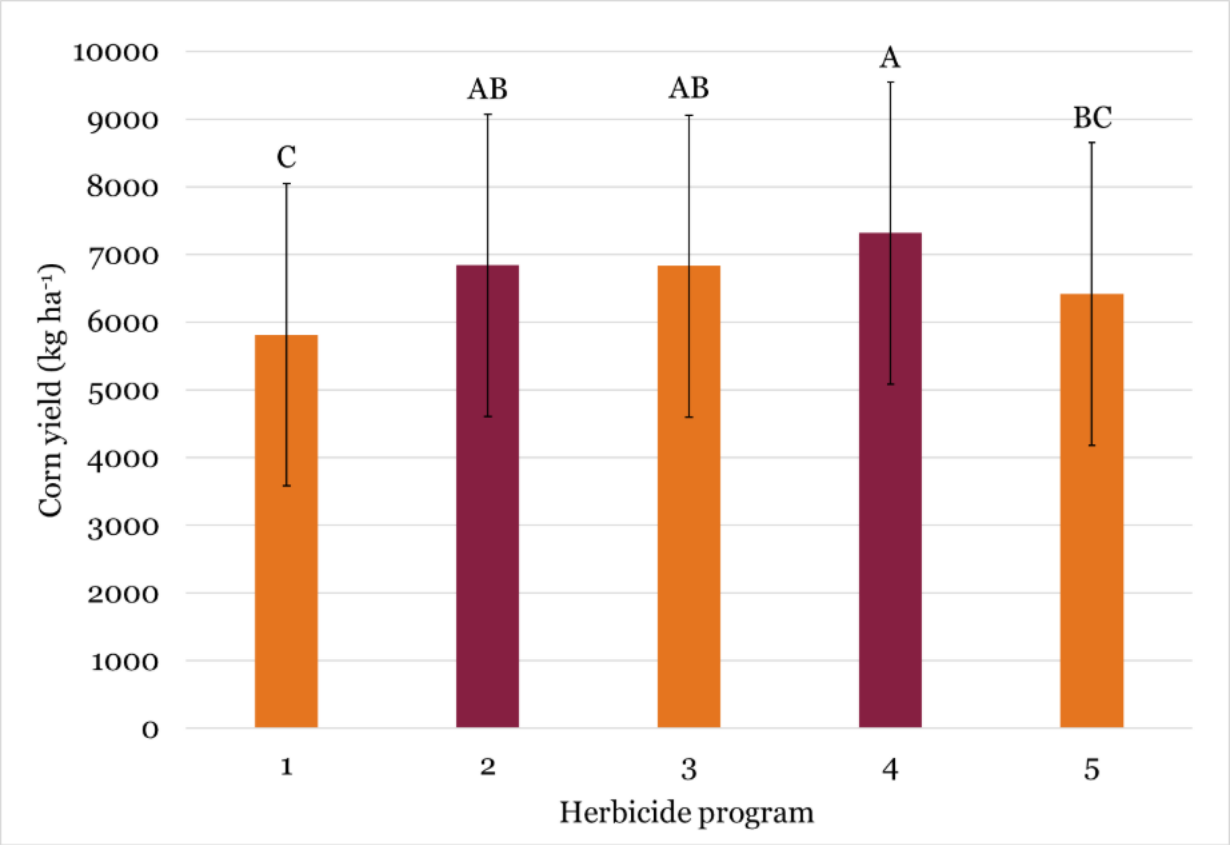

Figure 2.12. Corn yield LS means (with SE bars) by herbicide program from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The maroon bars indicate planting green herbicide programs while orange bars indicate planting brown programs. Herbicide programs are listed in Table 2.1.

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Comparing Black Oat and Cereal Rye Cover Crops for Biomass Accumulation and Weed Suppression Ability

Abstract

Cereal rye (*Secale cereale* L.) is a popular winter cover crop because of its ability to accumulate biomass and suppress weeds. However, cereal rye residues can create challenging planting conditions and immobilize nitrogen due to its high carbon to nitrogen (C:N) ratio. Thus, some farmers have begun substituting black oats (*Avena strigosa* S.). Our experiments compared 'Late Abruzzi' cereal rye to 'Cosaque' black oats cover crops in soybean (*Glycine max* (L.) Merr.) and corn (*Zea mays* L.), the latter of which included these grasses with and without hairy vetch (*Vicia villosa* R). Cover crop biomass data from both experiments demonstrated that cereal rye containing treatments accumulated more biomass at cash crop planting compared to treatments containing black oats. Both grasses had similar C:N ratios at planting (around 28:1). However, when hairy vetch was added, the C:N ratios were <25:1. Cover crop lignin content within the corn experiment followed a similar trend. However, in the soybean experiment, the black oats had a lower lignin content compared to cereal rye. Green cover results from the corn experiment demonstrated that black oat and cereal rye provided comparable coverage, but mixtures had greater overall coverage. Black oat containing treatments typically provided less weed suppression than cereal rye containing treatments for Palmer amaranth (*Amaranthus palmeri* S. Watson), common ragweed (*Ambrosia artemisiifolia* L.), large crabgrass (*Digitaria sanguinalis* L. Scop.), and total weeds. Ultimately, these results indicate that while black oats are comparable to cereal rye in terms of C:N ratio, lignin content, and green cover, cereal rye accumulates more biomass resulting in greater weed suppression. Thus, farmers may still be inclined to utilize a cereal rye monoculture or mixture as a winter cover crop.

Keywords: Biomass, C:N ratio, green cover, lignin content, weed suppression, Palmer amaranth (*Amaranthus palmeri* S. Watson)

Introduction

Cereal rye (*Secale cereale*) is the most common winter cover crop across the United States (Huddell et al., 2024). Cereal rye use has become popular due to its cold tolerance, low cost, erosion reduction, and its ability to produce large amounts of biomass (up to 15,000 kg ha^{-1}) (Camargo and Bagavathiannan, 2023; Huddell et al., 2024; Ryan et al., 2011). This surface biomass can ultimately result in weed suppression. Teasdale and Mohler (2000) found that in order to have 75% or greater weed control, 8000 kg ha^{-1} or more of cereal rye biomass was needed. Similarly, a study conducted in North Carolina found that cereal rye biomass of 9256 kg ha^{-1} resulted in weed control in the following soybean cash crop (Smith et al., 2011). Typically, cereal rye's biomass is slow to decompose due to its high carbon to nitrogen (C:N) ratio and lignin content (Pittman et al., 2020; Miller et al., 2022). Research has found that greater biomass persistence can lead to greater weed suppression longer into the growing season (Adhikari et al., 2024; Kumari et al., 2025; Pittman et al., 2020). While large amounts of biomass with a high C:N ratio (up to 80:1 (Reed et al., 2024)) can be beneficial in terms of weed control, these characteristics can also immobilize nitrogen (Sadeghpour et al., 2021). Nitrogen immobilization will occur with C:N ratios higher than 25:1 (Glaze-Corcoran et al. 2023). Immobilization of N can be harmful to the future cash crops, especially if they are nitrogen-needy crops such as corn or cotton (Williams et al., 2018). Still, cereal rye has become a staple cover crop across the United States because of the versatile role it plays for farmers.

Black oat (*Avena strigosa* S.) has been used as a cover crop in several cropping systems across the United States. This grass cover crop has become popular due to beneficial characteristics such as weed suppression and a lower C:N ratio compared to other grasses (Dial, 2014; Price et al., 2008). Black oats are able to reduce weed density in two main ways: their allelopathy and/or biomass. Allelopathy is defined as "the inhibitory or stimulatory effect of a plant on another species as a result of the release of chemicals into the environment" (Adler and Chase, 2007). Sturm et al., (2018) found that black oat's allelopathy can suppress weed density up to 28%. Moreover, black oats can reduce weed density via their surface residue (biomass) after termination. In the southeastern United States, a black oat cover crop can produce between 4487 to 7853 kg ha^{-1} of biomass (USDA-ARS-NSDL, 2005). To obtain a minimum of a 50% reduction in weed density in the Southeastern United States, Weisberger et al. (2023) states 6600 kg ha^{-1} of cover crop biomass is necessary meaning that black oats can suppress weeds with their biomass. Furthermore, black oat has a higher nitrogen content compared to other cereal crops such as cereal rye, oat (*Avena sativa*), and wheat (*Triticum aestivum*) (Bauer and Reeves, 1999). Thus, it tends to have a lower C:N ratio less of a tendency to immobilize nitrogen compared to higher C:N grasses like cereal rye (Clark, 2008; Dial, 2014; USDA-ARS-NSDL, 2005; Reed et al., 2024 Zhang et al., 2017). This lower C:N ratio may reduce persistence of black oat surface residues, potentially resulting in a shorter duration of weed suppression compared to cover crops like cereal rye. Recently, farmers have begun looking at black oat as an alternative grass cover crop that may better suit their farm's needs and not reduce nitrogen availability. While black oats tend to produce less biomass than cereal rye, its biomass can still provide numerous benefits to farmers.

Currently, direct comparisons between cereal rye and black oat for weed suppression are slim, especially within the mid-Atlantic region of the United States. Therefore, the objective of this research is to determine whether black oats would be a suitable replacement for cereal rye as a winter cover crop in the mid-Atlantic. Specifically, we will directly compare the weed suppression abilities, C:N ratio, lignin content, and biomass production of both cereal rye and black oats in soybean and corn systems in Virginia.

Materials and Methods

Study Sites

To assess and compare black oats and cereal rye for cover crop characteristics and weed suppression ability, two experiments were performed at two locations in two seasons for a total of four site-years per experiment. These studies were initiated in the fall of both 2023 and 2024 near Blacksburg, VA, USA at Kentland Farm (37°11'37"N 80°34'21"W) and near Blackstone, Virginia at the Southern Piedmont Agricultural Research and Extension Center (37°11'37"N 80°34'21"W). Kentland Farm soil is a fine-loamy, mixed, superactive, mesic Cumulic Hapludolls, classified as Ross. This area also falls within the New River's flood plain. The soil at the Blackstone site is an Applying coarse sandy loam and is taxonomically classed as fine, kaolinitic, thermic, Typic Kanhapludults. In 2023, the Blackstone location was previously forage sorghum. Prior to cover crop planting, the land was cut to around 10 cm tall with a tractor mounted rotary mower and disked twice. At cover crop planting, the fields were sprayed with a mixture of glyphosate (Roundup Powermax 3; Bayer Crop Science, St. Louis, MO, USA) at a rate of 1346 g ae ha^{-1} and glufosinate (Liberty 280 SL; BASF, Research Triangle Park, NC USA) at a rate of 788 g ai ha^{-1}. That same year in Blacksburg, the fields were prepared for planting by a

broadcast application of paraquat (Gramoxone® SL 2.0; Syngenta Crop Protection, Greensboro, NC, USA) at a rate of 841 g ai ha^{-1} with a 1% v v^{-1} of crop oil concentrate. In 2024, the fields at each location were previously fallow. Prior to cover crop planting in Blackstone, the fields were sprayed with glyphosate at a rate of 1,346 g ae ha^{-1} and subsequently disked. In Blacksburg that year, the site was tilled using a disk, cultipacked, and sprayed glyphosate and glufosinate prior to planting.

Treatments and Experimental Design

To evaluate the objectives, the first experiment had a corn cash crop and had four cover crop treatments: (1) Cosaque black oats, (2) Abruzzi cereal rye, (3) Cosaque black oats + Patagonia hairy vetch, and (4) Abruzzi cereal rye + Patagonia hairy vetch. The other experiment had a soybean cash crop and had two cover crop treatments: Cosaque black oats and Abruzzi cereal rye. All experiments used plots at least 7.6 m by 3.0 m and arranged in a randomized complete block design. Each treatment received four replications per location per year.

For Blacksburg, cover crop planting began on October 13th in 2023 and October 11th the following year. Blackstone cover crops were planted in 2023 and 2024 on October 4th and October 18th, respectively. All cover crops were drilled to around 2.5 cm deep. Cereal rye was planted at 84 kg ha^{-1}. Black oats were planted at 67 kg ha^{-1} in Blackstone both years and Blacksburg in 2024. In Blacksburg in 2023, they were planted at 54 kg black oats ha^{-1}. The hairy vetch for the corn experiment was planted at 22 kg ha^{-1} for all site years.

Crop Production Practices

At cash crop planting, the cover crops for both experiments in both years were terminated with a mixture of glyphosate at 1262 g ae ha^{-1} and glufosinate at 788 g ai ha^{-1}. Subsequently, the cash crops were planted.

In 2024, corn planting occurred on May 1st and May 8th at Blackstone and Blacksburg, respectively. The following year, it was planted in Blackstone on April 29th and in Blacksburg on May 5th. The corn, variety DKC110-10RIB with Acceleron Seed Treatment (Dekalb ; Bayer Crop Science, St. Louis, MO) was planted at 72376 seeds ha^{-1} on 76.2 cm row spacings. Immediately following planting, the experiment received 67 kg N ha^{-1} of starter fertilizer applied as 19-19-19. The corn was fertilized again with 168 kg N ha^{-1} in Blacksburg and 129 kg N ha^{-1} in Blackstone roughly one month later both years. Granular urea (46-0-0) was used for those later applications. At 1 month after planting POST herbicide application of *S*-metolachlor (1055 g ai ha^{-1}) (Dual II Magnum; Syngenta), glyphosate (1055 g ae ha^{-1}), and mesotrione (106 g ai ha^{-1}) in the form of Halex GT (Syngenta) was made.

Soybean planting in 2024 began on May 1st in Blackstone and May 8th in Blacksburg. In 2025, they were planted on April 29th and May 5th in Blackstone and Blacksburg, respectively. The soybean variety both years at either location was AG48XFO (Xtendflex by Asgrow; Bayer Crop Science, St. Louis, MO). Following planting, 0-25-25 fertilizer was applied to the fields at 56 kg P ha^{-1} and 56 kg K ha^{-1}. One month after soybean planting, a POST/layered PRE herbicide application consisting of glyphosate (1262 g ae ha^{-1}), glufosinate (788 g ai ha^{-1}), ammonium sulfate at 3400 g ha^{-1}, and *S*-metolachlor (1421 g ai ha^{-1}).

Data Collection

Due to variation in when farmers choose to terminate cover crops, cover crop biomass samples were collected from both experiments four weeks prior to, two weeks prior to, and at corn planting/cover crop termination. Biomass samples were taken using a randomly placed 0.25 m^2 quadrat within each plot. For the corn experiment, the biomass from plots containing two cover crop species was split by species. All samples were then dried to a constant weight,

weighed, homogenized, and a subsample was subjected to nutrient analysis for lignin, carbon, and nitrogen content via near-infrared spectroscopy.

Green cover data for both experiments was taken 4 weeks prior, 2 weeks prior, and at cash crop planting using Canopeo. To do this, a phone was held out at chest height and photographs of each plot were taken. Then, these images were processed by the Canopeo app (Canopeo App; Oklahoma State Department of Plant and Soil Sciences, Stillwater, OK) and data regarding the amount of green cover within the picture was output. Other research has also had success accurately estimating green cover using this app (Chhetri and Fontanier, 2021; Jáuregui et al., 2019; Shepherd et al., 2018).

Weed density data were collected one month after cash crop planting/cover crop termination on the most abundant weed species present. Data were also collected within those categories on weeds over 10 cm tall. Data were collected on the top five weeds present at all site-years in the corn experiments well as 2025 for the soybean experiment. In 2024, only the top three weed species at either site were counted in the soybean experiment. These data were collected using two randomly placed 0.5 m^2 quadrats in each plot. Palmer amaranth (*Amaranthus palmeri* S. Watson) was within the top weed species present at each location both years for both experiments.

For the corn experiment in Blacksburg in 2024, other species counted included non-rhizomatous Johnsongrass (*Sorghum halepense* (L.) Pers.), yellow nutsedge (*Cyperus esculentus* L.), Carolina horsenettle (*Solanum carolinense* L.), and morningglory species (*Ipomoea hederacea* and *lacunosa*). The same year in Blackstone, weed species included morningglory species, large crabgrass (*Digitaria sanguinalis* (L.) Scop.), common ragweed (*Ambrosia artemisiifolia*), and giant foxtail (*Setaria faberi*). The following year in Blacksburg, data was

collected on large crabgrass, giant foxtail, goosegrass (*Eleusine indica*), and yellow nutsedge. In Blackstone in 2025, species counted were large crabgrass, giant foxtail, common ragweed, and morningglory species.

For the soybean experiment in 2024, Blacksburg weed species counted were non-rhizomatous Johnsongrass and yellow nutsedge while Blackstone weed categories consisted of common ragweed and large crabgrass. The following year, giant foxtail, large crabgrass, yellow nutsedge, and goosegrass were the top weed species in Blacksburg. Weed species counted in 2025 in Blackstone were giant foxtail, morningglory species, common ragweed, and large crabgrass.

At the end of the growing season for the corn experiment, the corn was harvested using a Wintersteiger plot combine from the middle two interrows by at least 7.6 m of row in each plot. After harvest, the grain yield data were adjusted to 15.5% moisture. In 2024, yield was only taken from the Blackstone location and harvest occurred on September 10th. The following year, corn was harvested on September 23rd and October 6th from Blackstone and Blacksburg, respectively. Soybean yields were unable to be taken due to herbivory.

Data Analysis

The cover crop biomass, nutrient analysis, weed suppression, and grain yield data from both experiments were analyzed using JMP (JMP Pro 18.0.2; SAS Institute, Inc., Cary, NC, USA). Cover crop species was the only fixed effect for cover crop biomass at corn or soybean planting, weed suppression analyses, green cover, and yield when applicable. Statistical analysis was only conducted on weeds that were present at more than two site-years. Total weeds were also analyzed. Prior to analysis, data were transformed to meet a normal distribution. If transformations did not improve normality, the data were left untransformed. For all analyses,

location was treated as a random variable and replication was treated as a random variable nested within location. Data were subjected to analysis of variance (ANOVA). Subsequently, means were separated using a Student's t-test ($p \leq 0.05$) or subsequent regression analysis was conducted.

Results and Discussion

Corn Experiment

Cover Crop Biomass Accumulation

Cover crop, timing, and their interaction were significant within the final model. Thus, a subsequent regression analysis was conducted to see cover crop biomass accumulation throughout the growing season (Figure 3.1). One month prior to corn planting, both cover crop mixtures had accumulated greater quantities of biomass compared to the monocultures. Two weeks later, biomass continued to increase for all cover crops but the mixtures still had produced greater amounts of biomass. Finally, at corn planting, the regression demonstrated that the hairy vetch and cereal rye mixture had accumulated the most biomass compared to the black oats and hairy vetch mixture and the two monocultures. At this time, the average amount of biomass accumulated by cereal rye, black oats, the cereal rye + hairy vetch mixture, and the black oats + hairy vetch mixture at corn planting was 4572, 3931, 5756, and 4660 kg ha^{-1}, respectively.

Previous research supports our finding that as time progressed cereal rye and hairy vetch mixture produced more biomass compared to cereal rye alone (Hayden et al., 2012). A meta-analysis conducted by Thapa et al. (2018) reported that a hairy vetch and cereal rye mixture will produce 63 and 21% more biomass than monocultures of hairy vetch and cereal rye, respectively. At corn planting, our cereal rye and hairy vetch mixture had accumulated about 5756 kg ha^{-1} of

biomass which was on par with the average of 6000 kg ha^{-1} (Thapa et al., 2018). At this time, the cereal rye monoculture had produced 4572 kg ha^{-1} of biomass which is above the average of 3428 kg ha^{-1} (Huddell et al., 2024). Currently, there is little research discussing season-long biomass accumulation by a black oat cover crop in the mid-Atlantic. However, other popular cereal cover crops, specifically wheat, cereal rye, and oats, typically average ~2800, 3428, and ~3000 kg ha^{-1}, respectively (Huddell et al., 2024; Ruis et al., 2019). Thus, in comparison with the biomass from other cereals, our black oat biomass average at corn planting, 3932 kg ha^{-1}, appears to be a comparable amount of cover crop biomass for this species.

Green Cover

Cover crop was a significant ($p<0.010$) main effect for green cover at each timing (Figure 3.2). Subsequent regression analysis did not support this information, thus, ANOVA results are being discussed. ANOVA analysis demonstrated that across sampling timings the cover crop mixtures provided greater percentages of green cover compared to both monocultures. At planting, the cereal rye and black oat monocultures provided 48 to 50% green cover whereas the mixtures produced 85 to 89% coverage.

Overall, the cover crop mixtures that included hairy vetch provided the more green cover compared to the monocultures. Neither black oat nor cereal rye when mixed with hairy vetch provided more green cover than the other. This trend was similar to biomass. More green cover by the mixtures may be due to hairy vetch's vine-like lateral growth habit compared to both cereal rye and black oats which grow mostly upright (Teasdale et al., 2004). Moreover, a study conducted by Lawson et al. (2015) also found that a hairy vetch and cereal rye cover provided significantly greater ground cover compared to cereal rye alone. Cover crops having a better amount of ground coverage can lead to more protection from raindrop impact, subsequently

leading to reduced soil erosion and nutrient runoff and increased stability of soil aggregates (Prabhakara et al., 2015). Ultimately, farmers in the mid-Atlantic region who are looking for erosion prevention and associated benefits should look more towards integrating a hairy vetch and either black oats or cereal rye mixture as a cover crop rather than a black oat or cereal rye monoculture.

Carbon to Nitrogen Ratio

Cover crop, sampling timing (weeks before planting), and their interaction were significant in the final model (Figure 3.1). Subsequent regression analysis was conducted and suggested that as time progressed, the C:N ratios of the cover crop monocultures were higher than that of the mixtures. At corn planting, the cereal rye monoculture had acquired the highest C:N ratio (35:1), followed by the black oat monoculture (31:0), and then the cereal rye + hairy vetch mixture (17:1), and lastly the black oat + hairy vetch mixture (16:1). Moreover, the cereal rye and black oat regression lines had somewhat steeper slopes compared to the cover crop mixtures which did not have a significant linear association between C:N ratio and cover crop species throughout the sample timings.

These findings coincide with previously conducted research by Poffenbargeret al. (2015) that determined as hairy vetch biomass increased from 0 to 100% within a hairy vetch and cereal rye mixture, the C:N ratio decreased from 83:1 to 16:1. At planting the cereal rye + hairy vetch mixture and cereal rye monoculture had C:N ratios of 15.6: and 27.9:1, respectively. Having a C:N ratio <25:1 results in a reduced risk for nitrogen immobilization and faster biomass decomposition (Glaze-Corcoran et al., 2023; Jahanzad et al., 2016). A similar trend was seen with the black oat monoculture and mixture at corn planting. Moreover, a hairy vetch and cereal rye or black oat cover crop will release nitrogen earlier in the season because of the hairy vetch's

faster decomposition rate due to its lower C:N ratio (Miguez and Bollero, 2005; Sievers and Cook, 2018). However, because the cereal species typically have C:N ratios >25:1, their biomass will not break down as quickly, ultimately leaving biomass on the surface which may provide benefits such as reduced soil erosion and increased weed suppression (Langdale et al., 1991; Sievers and Cook, 2018; Teasdale, 1996). Furthermore, the black oat and cereal rye monoculture had similar C:N ratios at the final sampling date, indicating that black oats may not reduce nitrogen immobilization as originally hypothesized, but could be utilized as a substitute for cereal rye. Overall, farmers in the mid-Atlantic region who are interested in providing their cash crop with nitrogen earlier in the growing season and reducing potential nitrogen immobilization may look towards integrating hairy vetch into their cereal rye or black oat monoculture cover crop.

Lignin Content

Cover crop and timing (WBP) were significant for cover crop lignin content ($p<0.005$) (Figure 3.1). When comparing the least squared means of the different cover crop species, the two grass and hairy vetch mixtures had significantly higher lignin contents compared to the two monocultures. The black oat and cereal monocultures were statistically not different from each other. Cereal rye and black oat lignin contents were 3.7% and 3.4% at corn planting, respectively. The ANOVA demonstrated that, on average, the cover crop mixtures tended to have greater lignin contents compared to the cover crop monocultures and lignin content at corn planting was significantly higher compared to two weeks and four weeks prior to planting.

Previous research has determined that a greater lignin content and greater C:N ratio can result in slower cover crop residue breakdown and ultimately a slower release of nitrogen or other nutrients (Sainju et al., 2003; Vigil and Kissel, 1991). Oftentimes, grass type cover crops

with greater C:N ratios and lignin content breakdown significantly slower than leguminous cover crops (Adhikari et al., 2024; Talbot and Treseder, 2012). This can potentially cause problems for farmers who are growing nitrogen needy cash crops such as corn. A slowed release of cover crop nitrogen can cause farmers to increase nitrogen fertilizer rates to counteract the reduced nitrogen availability (Menker and Gatibomi, 2021). Thus, according to our lignin percentage results, the use of cover crop mixtures would immobilize the most nitrogen due to the higher lignin contents. Therefore, when only observing lignin contents of cover crops, it appears that the cover crop monocultures would be the more ideal choice for corn farmers in Virginia. However, research has also found a correlation between the lignin to nitrogen ratio and increased biomass decomposition (Adhikari et al., 2024; Li et al., 2021). When taking this ratio into consideration, the cover crop mixtures, which have greater nitrogen contents compared to the monocultures, may be better for farmers looking to reduce nitrogen immobilization. Overall, while cover crop monocultures tended to have lower lignin concentrations at all timings, the grass + hairy vetch mixtures may be ultimately better for reducing nitrogen immobilization prior to a corn cash crop.

Weed Suppression

Total weeds as well as Palmer amaranth, yellow nutsedge, morningglory species, common ragweed, and giant foxtail were analyzed because they had data from two more than two site years. Cover crop was a significant factor for Palmer amaranth ($p=0.007$), large crabgrass ($p<0.001$), common ragweed ($p=0.022$), and total weeds ($p<0.001$) (Figure 3.3). Results from each weed species and total weeds showed a common theme that the black oat monoculture was in grouping with the least amount of weed suppression. On the contrast, the cereal rye + hairy vetch mixture was in the top performing statistical grouping for each weed

species as well as total weeds. The cereal + hairy vetch mixture was also within this group for common ragweed and large crabgrass. Cover crop was also a significant effect for the proportion of total weeds over 10 cm (Figure 3.4). However, cover crop species was not significant for the proportion of Palmer amaranth greater than 10 cm.

Oftentimes the more biomass a cover crop can generate throughout the season, the better its weed suppression abilities are (Osipitan et al., 2019), which was found in our study. We typically saw the cereal rye + hairy vetch mixture, which had the greatest biomass accumulation at corn planting, within the uppermost weed suppressing group regardless of weed species or height. With that being said, the black oats + hairy vetch mixture was also within this highest grouping for large crabgrass and common ragweed. It was the second highest biomass producing cover crop at corn planting. Regardless of the cover crop treatment, biomass needed for a 50% reduction in weed density in the Southeastern region of the United States, about 6000 kg ha^{-1}, (Weisberger et al. 2023) was not achieved. Therefore, while our results indicate the best cover crop treatment was the cereal cover crop + hairy vetch mixture, this may have differed if more robust biomass production was achieved. The allelopathic abilities of both cereal rye and black oats have also been found to aid in their weed suppression (Shilling et al., 1985; Sturm et al., 2018). A study conducted by Barnes et al. (1986) found that cereal rye residue, when compared with a non-allelopathic residue, reduced redroot pigweed (*Amaranthus retroflexus* L.) and barnyard grass (*Echinochloa crus-galli* (L.) P. Beauv.) biomass by 55% and 74%, respectively. Similarly, Gerhards et al. (2024) found aqueous extracts from black oats inhibited weed germination by 77.9% compared to oilseed radish (72.4%) and multiple other less known cover crops. This reduction in biomass was mainly credited to the cereal rye's allelopathy (Barnes et al., 1986). The allelopathic abilities of these two cover crops may also have contributed to their

weed suppression abilities in this study. Overall, farmers in the mid-Atlantic region should consider integrating a cereal cover crop + hairy vetch mixture if they are aiming to increase their overall weed suppression early in the growing season.

Yield

Cover crop was a significant effect on corn yield ($p=0.014$) (Figure 3.5). Both cover crop mixtures were among the top statistical grouping. Within each grass, the addition of hairy vetch increased corn yield between 16.4% and 14.8%. The cereal rye + hairy vetch mixture yielded more than both monocultures. This trend indicates that including hairy vetch resulted in greater corn yield, which is likely due to the N contribution or lack of N immobilization by including the legume.

Previous literature found that the presence of a leguminous cover crop prior to corn, along with a nitrogen fertilizer rate of 100-199 kg ha^{-1}, resulted in a 17% increase compared to no cover crop. However, other data shows that regardless of whether the cover crop is a mixture or monoculture, corn yields are unphased (Waring et al., 2023). Our results showed that while the addition of hairy vetch did increase yields, it was not always statistically different from the cereal rye monoculture. Furthermore, research has also determined that the nitrogen provided by leguminous cover crops can decrease fertilizer costs without sacrificing corn yields (Marcilllo et al., 2024). This may be another benefit to adding hairy vetch to a cereal rye or black oat cover crop prior to corn. Ultimately, for farmers in Virginia, adding hairy vetch to a cereal rye monoculture would provide greater corn yields compared to both cereal rye or black oat monocultures while simultaneously having the potential to reduce fertilizer costs.

Soybean Experiment

Cover Crop Biomass Accumulation

Cover crop, timing, and their interaction were significant effects. A regression analysis was run subsequently to better portray the data over time (Figure 3.5). The regression demonstrates that both cover crop species appear to have similar biomass amounts at both 4 weeks prior to and 2 weeks prior to soybean planting. However, at soybean planting, the cereal rye cover crop seemed to have accumulated significantly more biomass compared to the black oat cover crop. At soybean planting, the cereal rye cover crop had around 4600 kg ha^{-1} while the black oat cover crop only had around 3400 kg ha^{-1} of biomass.

In the Coastal Plain region of the Southeastern United States, black oats typically produce about 2244 kg ha^{-1} of biomass while cereal rye averages around 4487 kg ha^{-1} (Gaskin et al., n.d.). Our black oat and cereal rye cover crops both produced higher than average biomass potentially because our cover crops were not grown in sandy soil like those reported by (Gaskin et al. (n.d.). Moreover, typically with cover crops, the more biomass produced, the better benefits the farmer will see (Balkcom et al., 2018; MacLaren et al., 2019). Thus, more benefits may be associated with cereal rye in our study because of this. Overall, a black oat cover crop may not be the best choice for mid-Atlantic farmers who are looking to their cover crop biomass accumulation.

Green Cover

Regardless of timing, cover crop was not a significant main effect effect for the percentage of green cover ($p>0.05$). Timing was significant according to ANOVA, but subsequent regression analysis did not result in a significant linear trend. Thus, both a black oat and cereal rye cover crop provided similar amounts of green cover. 4 weeks prior to soybean planting, green cover averaged 46.3%. Two weeks later, green cover averaged 51.3%. Finally, at soybean planting, green cover averaged 42.5%.

Based on the previously mentioned biomass accumulation data, these results were unexpected. In the past, research has determined that there is a correlation between biomass production and overall ground cover (Prabhakara et al., 2015). Thus, we expected to see greater ground cover via the cereal rye cover crop due to its more robust biomass production, but this was not the case. This result may be because more biomass was needed to see distinct differences between the two grass species. A ground cover of 30% can control around 50% of soil erosion caused by rain. Regardless of sampling times, both cover crops in this study provided greater than 30% ground cover indicating that they would reduce soil erosion by >50% (Prabhakara et al., 2015). In the end, Virginia farmers looking to reduce erosion and have at least 40% ground cover can plant either a black oats or cereal rye cover crop.

C:N Ratio

Timing was the only significant factor ($p<0.05$) for cover crop C:N ratio. A subsequent regression analysis was conducted on this data to better portray its trend over time (Figure 3.5). This analysis demonstrated that the C:N ratio of the cereal rye cover crop was significantly different between each of the three sample timings. The LS means for the black oat cover crop were also analyzed. These demonstrated a similar trend of increasing over time. At soybean planting, both cover crop's C:N ratio appeared to be around 28:1.

The findings of this experiment did not align with previous research. In the past, black oats have been found to have a C:N ratio of around 28:1 whereas cereal rye has been found to have a C:N ratio of around 20:1 at the mid-boot stage and later >40:1 at maturity (Reed et al., 2024). Thus, it was unusual to see that in this study, the cover crops had similar C:N ratios. We may not have seen this distinct difference between the cereal rye and black oats because the cereal rye had not fully matured at soybean planting. As cereal rye matures, it accumulates more

carbon within its stem which plays a key role in its high C:N ratio (Roth and Waite, 2021). Furthermore, C:N ratios higher than 40 to 80:1 have been shown to immobilize nitrogen (Williams et al., 2018). However, neither monoculture in this study produced a high enough C:N ratio to significantly immobilize nitrogen. Overall, this study's results indicate that farmers in Virginia worried about their cover crop's potential nitrogen immobilization or C:N ratio could interchangeably use black oats and cereal rye monocultures if they are terminated prior to maturity.

Lignin

Cover crop, timing, and their interaction were significant ($p<0.020$) in the final model. To better demonstrate this interaction, a regression analysis was conducted (Figure 3.5). The regression line shows the lignin content of the cereal rye cover crop increasing over the three sample timings. The LS means associated with those sample timings were also included for the black oat cover crop. There did not appear to be a significant trend amongst these data points. At soybean planting, the cereal rye and black oat cover crops appeared to have lignin contents of around 2.4% and 3.8%, respectively.

Lignin content has been reported to be one of the predictors of decomposition rates and nitrogen immobilization of cover crops (Quemada and Cabrera, 1995; Jahanzad et al., 2016). Typically, a majority of the lignin within plants can be found in the stems and thus grass cover crops tend to have higher lignin contents compared to leguminous cover crops (Quemada and Cabrera, 1995). Lignin also accumulates more as plants reach maturity (Bhorade et al., 2023; Zhu and Barros, 2025). Our results show that at cash crop planting, cereal rye has a significantly higher lignin concentration compared to black oats. Thus, while both monocultures had similar C:N ratios, cereal rye's higher lignin content could lead to slower decomposition rates and

nitrogen release to the following cover crop (Adhikari et al., 2024). Slower decomposition rates immobilize nitrogen which can inhibit weed growth (Kruidhof et al., 2009). Moreover, a longer decomposition rate can also aid in weed suppression due to the cover crop's residual residue or via slower allelochemical release (Kruidhof et al., 2009; Teasdale, 1996). In theory and based on our results, the use of a cereal rye as a winter cover crop would be more optimal for soybean farmers in Virginia who are less concerned about nutrient release and more interested in early season weed control.

Weed Density

Cover crop species was significant ($p<0.05$) for Palmer amaranth, large crabgrass, and total weeds (Figure 3.6). The cereal rye cover crop had better weed suppression for all weed species as well as for total weeds compared to the black oat cover crop. For Palmer amaranth, there was a ~9% difference in weed suppression between the black oats and cereal rye cover crops. The use of cereal rye resulted in an 18% large crabgrass reduction compared to black oats. As for total weeds, cereal rye had, on average, 127 less weeds m^{-2} than the black oats treatment. Cover crop was not significant for the proportion of weeds >10 cm for any species or total weeds. Thus, while cereal rye reduced weed density more than black oats, both cover crops resulted in similar weed heights.

The weed suppression ability of a cover crop heavily depends on its biomass production (Osipitan et al., 2019). In this study, cereal rye accumulated significantly more biomass at soybean planting compared to black oats. Thus, the cereal rye treatment resulted in better weed suppression across the board. Little research has been conducted on the amount of black oats biomass needed for adequate weed suppression in the mid-Atlantic region. However, McKenzie-Gopsill et al. (22) found that 1200 kg ha^{-1} of cover crop biomass can reduce weed density by

50%. However, as cereal rye's residue levels increase, weed suppression levels increase as well (Ryan et al., 2011). The weed suppression from either cover crop could have been in part due to their allelopathy; however, this was not evaluated within this study (Grint et al., 2022; Sturm et al., 2018). Overall, this study's findings demonstrated that the more lignified cereal rye biomass provided better general weed suppression compared to black oats. Therefore, Virginia farmers looking to optimize early season weed suppression in soybean systems may favor the use of cereal rye over black oats.

Figures

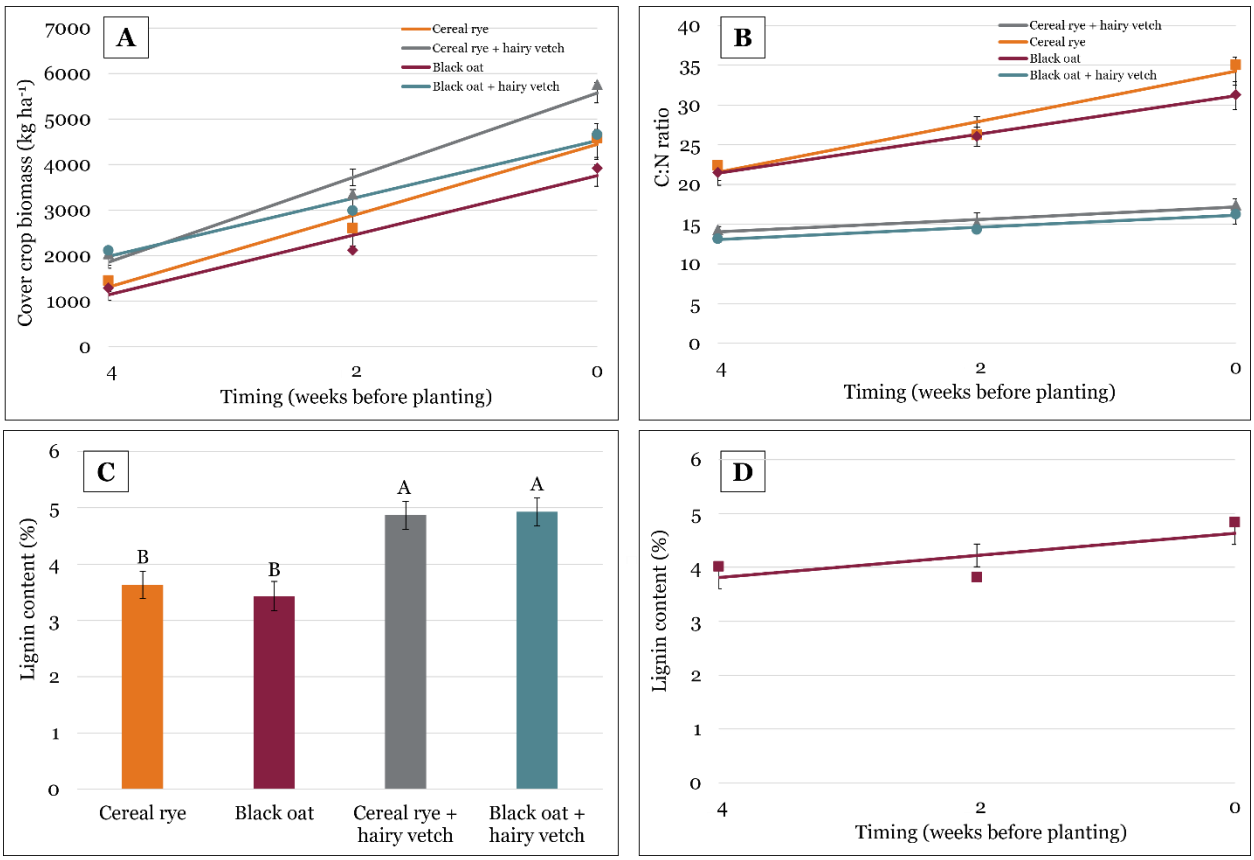

Figure 3.1. Cover crop biomass (A), C:N ratio (B), lignin content (C), and green cover (D) from field experiments in Virginia in 2023 to 2025. When a significant interaction of cover crop by sampling timing was significant, regression lines are displayed with LS means and SE bars at 4 weeks prior to, 2 weeks prior to, and at cash crop planting B.

A). Biomass regression equations are as follows: 1. cereal rye biomass = 4445.9 – 784.9*timing ($p<0.001$; $R^2=0.65$); 2. cereal rye + hairy vetch biomass = 5573.8 – 929.4*timing ($p<0.001$; $R^2=0.80$); 3. Black oat biomass = 3758.8 – 655.3*timing ($p<0.001$; $R^2=0.67$); 4. black oat + hairy vetch = 4528 – 636.3*timing ($p<0.001$; $R^2=0.49$).

B). C:N ratio regression equations are as follows: 1. cereal rye + hairy vetch's C:N ratio =34.2 – 3.18*timing ($p<0.001$; $R^2=0.49$); 2. cereal rye C:N ratio = 17.2 – 0.79*timing ($p=0.013$,

R^2=0.13); black oat C:N ratio =31.2-1.35*timing ($p<0.001$; R^2=0.32); black oat + hairy vetch C:N ratio = 16.1 – 0.77*timing ($p = 0.005$; R^2=0.16).

C). Lignin content at corn planting LS means (with SE bars) by cover crop program. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$).

D. Regression equation is as follows: Lignin content = 4.6 – 0.20*timing ($p=0.013$; R^2=0.03).

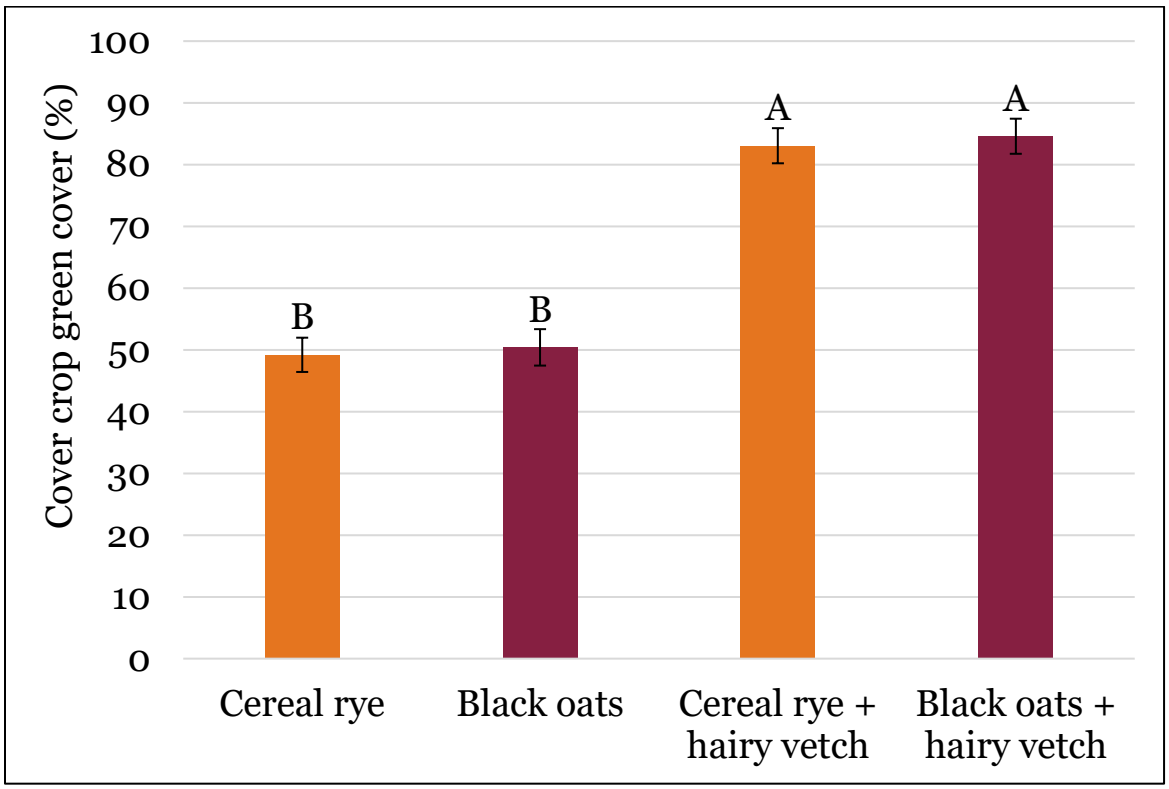

Figure 3.2. Green cover at corn planting LS means (with SE bars) by cover crop program. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate cereal rye monocultures or mixtures while maroon bars indicate black oat monocultures or mixtures.

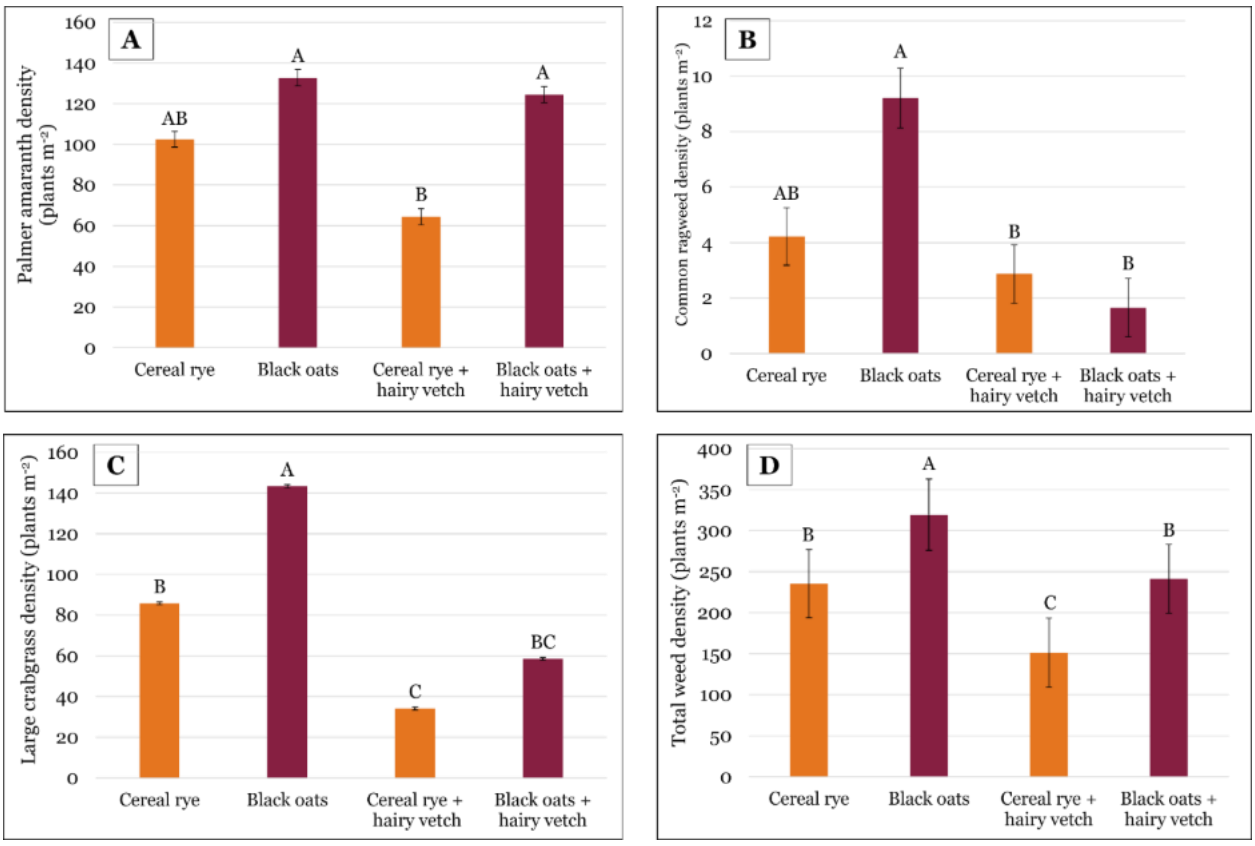

Figure 3.3. Significant LS means (with SE bars) by cover crop for Palmer amaranth (A), common ragweed (B), large crabgrass (C), and total weeds (D). Data from each graph were taken from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$) for each individual figure. Orange bars represent cereal rye monocultures or mixtures while maroon bars indicate black oat monocultures or mixtures.

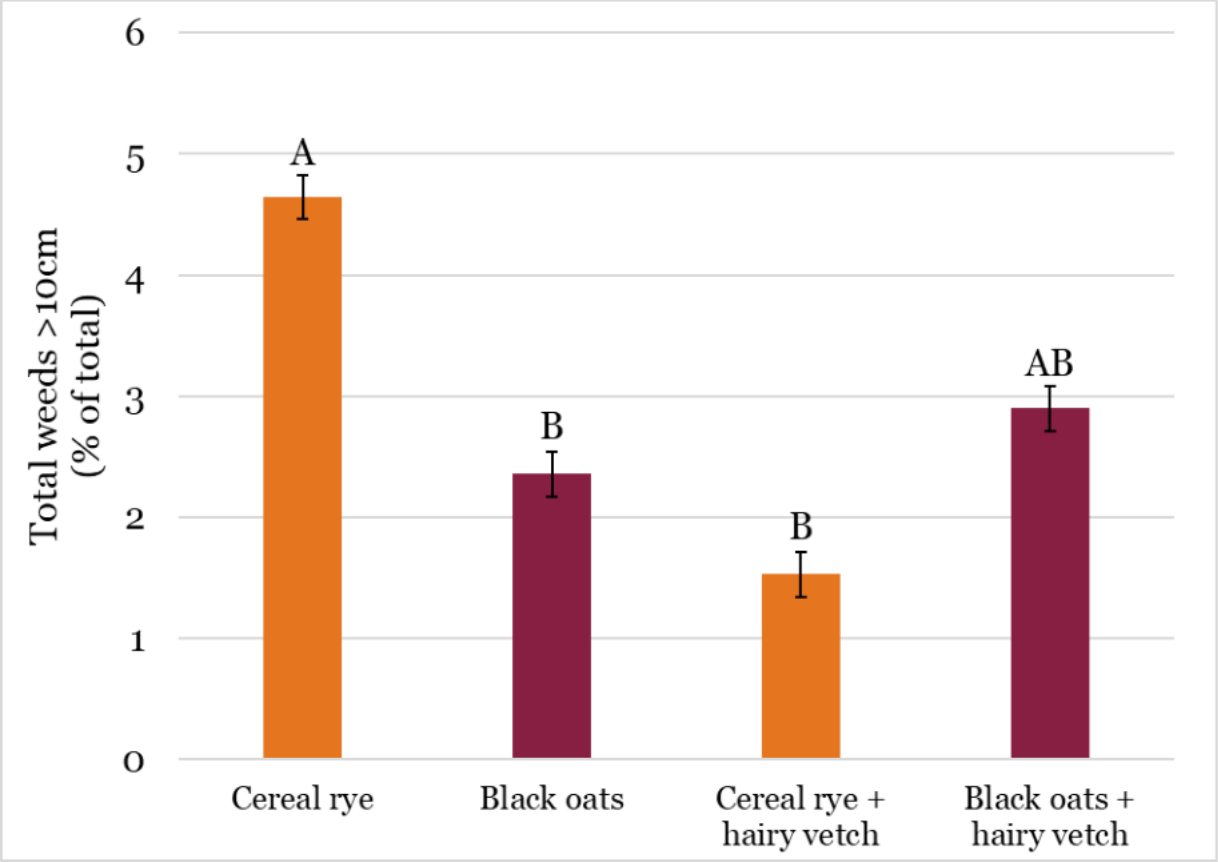

Figure 3.4. LS means (with SE bars) of total weeds >10 cm by cover crop program from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate cereal rye monocultures or mixtures while maroon bars indicate black oat monocultures or mixtures.

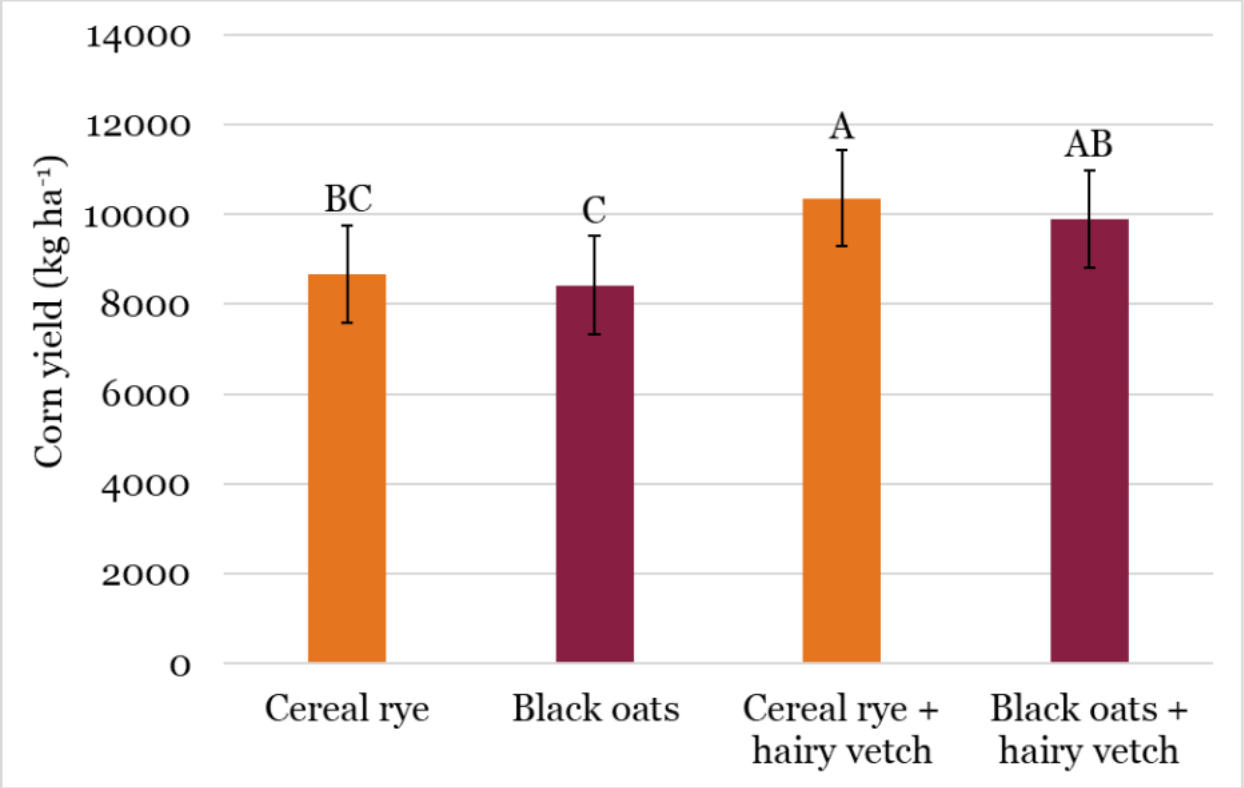

Figure 3.5. Corn yield LS means (with SE bars) by cover crop program from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). Orange bars indicate cereal rye monocultures or mixtures while maroon bars indicate black oat monocultures or mixtures.

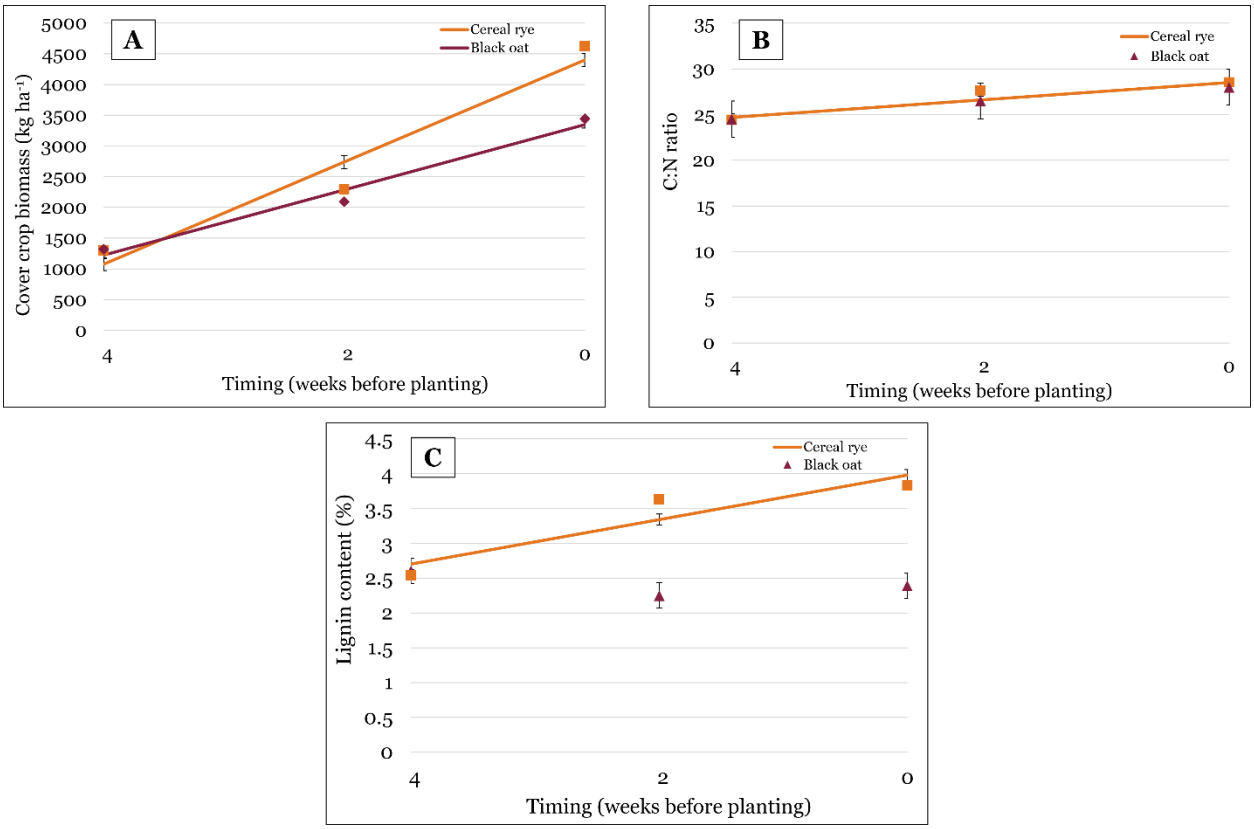

Figure 3.5. Cover crop biomass (A), C:N ratio (B), and lignin content (C) from field experiments in Virginia in 2023 to 2025. When a significant interaction of cover crop by sampling timing was significant, regression lines are displayed with LS means and SE bars at 4 weeks prior to, 2 weeks prior to, and at cash crop planting B.

A) Cover crop biomass regression equations are as follows: 1. cereal rye biomass = 4400 - 831*timing ($p<0.001$; $R^2=0.57$); 2. black oat biomass = 3347 - 530*timing ($p<0.001$; $R^2=0.64$).

B). Cover crop C:N ratio regression equation is as follows: cereal rye + hairy vetch biomass = 28.5 - 0.95*timing ($p=0.015$; $R^2=0.06$).

C). Cereal rye lignin content regression equation is as follows cereal rye lignin content (%) =4.62-0.47*timing ($p=0.001$; $R^2=0.21$).

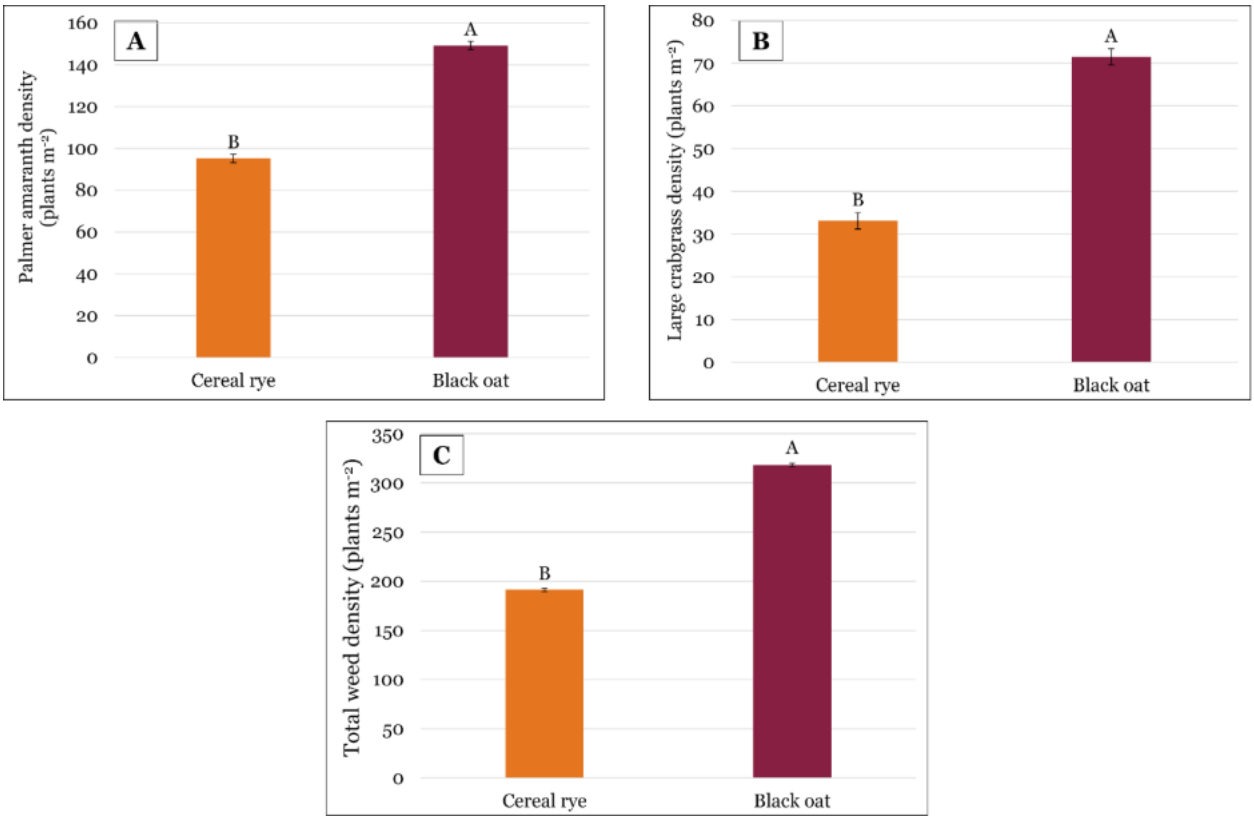

Figure 3.6. Palmer amaranth (A), large crabgrass (B), and total weed (C) density averages by cover crop from field experiments in Virginia in 2023 to 2025. Letters indicate significant differences according to Student's T-test ($p \leq 0.05$). The orange bar indicates a cereal rye cover crop while the maroon bar indicates black oats cover crop.

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